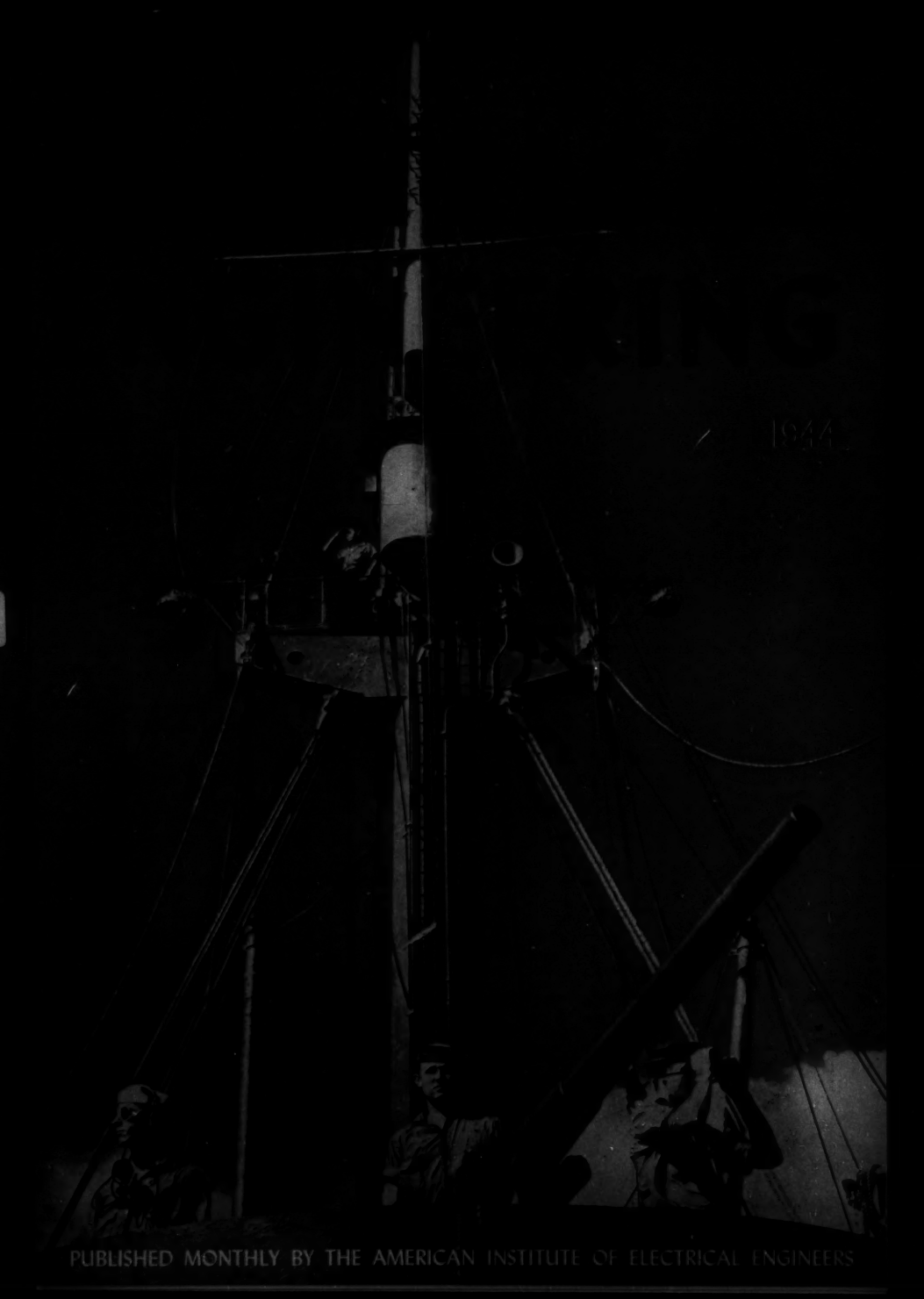

PUBLISHED MONTHLY BY THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

THE LITTLE GLASS TUBE THAT HELPS KEEP PLANE VOLTAGES CONSTANT...

Available for Government war emergency use only.

IT doesn't look exciting but this little Corning precision tube is flying in our planes to help them out-perform those of our enemy. It is the "heart" of an important piece of apparatus called a carbon pile voltage regulator.

As the name implies, the function of this equipment is to provide even, continuous voltage regulation without lag or fluctuation. This is accomplished by pressure exerted on a stack of carbon discs.

The tube which contains these discs must be smooth, accurate in dimensions and capable of withstanding high temperatures. For it, Eclipse-Pioneer engineers have chosen a precision ground Pyrex tube with an outside diameter of .6245 plus 0 minus .001 inches and an inside diameter of .435 plus or minus .002 inches. Tolerances unheard of five years ago except for optical purposes!

Perhaps Corning's "know how" in glass may some day be of use to you, too. Under the Army-Navy "E" flag at Corning you'll find glasses with high dielectric strength, extreme resistance to thermal or mechanical shock or any combination of these qualities needed to fit your particular requirements. Just to keep you informed we'd like you to have a free study called "There Will Be More Glass Parts In Post-War Electrical Products." Write for your copy to the Electronic Sales Dept. N-5, Bulb and Tubing Division, Corning Glass Works, Corning, New York.

Photo Courtesy Eclipse-Pioneer Division of Bendix Aviation Corporation

CORNING *means* Research in Glass

Electronic Glassware

T.M.REG. CORNING U.S. PAT. OFF. T.M.REG. PYREX U.S. PAT. OFF.

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when Post-War Plans create new magnet wire problems ... CALL A BELDEN WIRE ENGINEER

Those post-war appliances are coming! And they will be different in appearance ... in specifications ... in performance.

Many unusual magnet wire problems are sure to develop. Coils may be smaller, ratings higher, or clearances less.

You may run into many unexpected winding machine difficulties in post-war production.

BALANCED INSULATION

Belden Magnet Wires have Balanced Insulation. Essential electrical and mechanical characteristics are combined in balanced proportions, thus reducing rejections due to poor insulation. For lowest overall winding costs, specify Belden.

Whatever your problem, call in a Belden Wire Engineer. Belden Wire Engineering Service covers all phases of magnet wire application from basic specifications to production.

Over a third of a century of technical experience is available to you. Use it ... save time and money ... and cut overall winding costs.

Belden Manufacturing Company, 4635 W. Van Buren St., Chicago 44, Illinois

Belden Magnet Wires

NATURAL AND SYNTHETIC ENAMELS AND TEXTILE INSULATIONS

ELECTRICAL ENGINEERING. Published monthly by the American Institute of Electrical Engineers; publication office 20th & Northampton Streets, Easton, Pa. Editorial and advertising offices, 33 West 39th Street, New York 18, N. Y. Subscription $12 per year plus extra postage charge to all countries to which the second-class postage rate does not apply; single copy $1.50. Entered as second-class matter at the Post Office, Easton, Pa., under the Act of Congress of March 3, 1879. Accepted for mailing at special postage rates provided for in Section 538, P.L. & R. Act of February 28, 1925.
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HELP HIM GET THAT

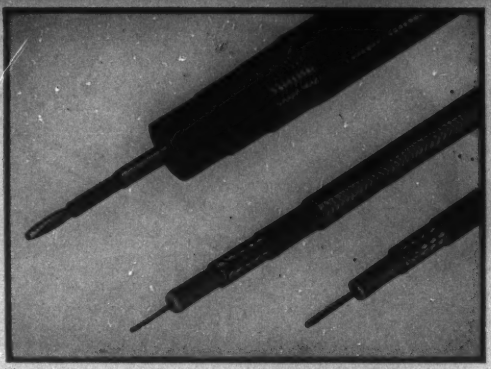
LONG DISTANCE CALL

THROUGH TONIGHT

You can do it by not using Long Distance between 7 and 10 P. M. Those are the night-time hours when many service men are off duty and it's their best chance to call the folks at home.

BELL TELEPHONE SYSTEM

Typical Okonite Cables for electronic uses



THE APPLICATION OF SYNTHETIC INSULATIONS TO { Co-Axial Cables / High Voltage Cables / High Frequency Cables

The success of Okonite cables designed for today's electronic applications depends on work started over 10 years ago by Okonite Research engineers when they first commenced to use synthetics. Some types such as neoprene, koroseal, vinylite, and thiokol were soon found to have immediate applications, although there seemed to be no ready application for certain other types which had unusual, distinctive characteristics.

With the start of the war and the rapid progress made in extending the range of electronic equipment, cables were demanded having insulations with characteristics quite different from those used for ordinary power applications. The early research only then began to bear fruit and some of these new synthetics provided the answers to other war-time problems. The accompanying tabulation lists several of the synthetics available for use on cables and indicates their possibilities. Some already are used daily in our regular cable production. Others are only awaiting a need as yet unidentified. Perhaps you have a problem we can solve with these or other synthetics. Why not state your cable needs and let Okonite engineers make recommendations. We have both the equipment and the "know how" that can help provide a solution. Address, The Okonite Company, Passaic, N. J.

Typical Synthetic Materials with Promising Characteristics for Use on Electronic Wires and Cables

Name	Chemical Type	Use on Cable	Dielectric Constant	Power Factor	Dielectric Strength	Resistivity	Physical Properties	Oil Resistance	Resistance to Ozone and Sunlight
BUTYL RUBBER	Isobutylene-Diolefin Copolymer	Insulation	E	E	F	E	G	P	G
POLYBUTENE	Isobutylene Polymer	Insulation	E	E	F	E	F	P	E
POLYTHENE	Ethylene Polymer	Insulation	E	E	E	E	E	F	E
KOROSEAL	Plasticized Vinyl Chloride Polymer	Insulation or Jacket	F	F	G	F	G	E	E
VINYLITE	Plasticized Vinyl Chloride Vinyl Acetate Copolymer	Insulation or Jacket	F	F	G	F	G	E	E
BUNA S	Butadiene-Styrene Copolymer	Insulation or Jacket	G	G	G	G	G	F	F
BUNA N	Butadiene-Acrylonitrile Copolymer	Jacket	F	F	F	F	G	G	F
NEOPRENE	Chloroprene Polymer	Jacket	F	F	F	F	G	G	E
THIOKOL	Organic Polysulfides	Jacket	P	P	P	P	F	E	E

E—Excellent, G—Good, F—Fair, P—Poor. Physical properties include tensile strength, elongation, modulus, toughness and abrasion resistance.

OKONITE SINCE 1878 INSULATED WIRES AND CABLES

3633

Aircraft Brush Life Increased Ten Times!

EXPERIMENTS carried through a step that no one had taken before revealed to National Carbon Company, Inc., research engineers the *cause* of the rapid disintegration of aircraft brushes at high altitudes.

Once the cause of the trouble was known, the remedy could be found. And today, eight new "National" brush grades for aircraft generators, motors, and other rotating electrical equipment are giving *ten times* the service life once obtained . . . from sea level up into the stratosphere.

A small thing . . . of tremendous importance . . . cleared the way for this National Carbon development. It consisted of *drying* the refrigerated, rarefied, test chamber air in which performance of aircraft brushes was analyzed.

No one had done that before for carbon brushes . . . actually brought the stratosphere down to earth so that failing brushes could be closely studied . . . so needed changes could be made . . . until the problem was solved.

This type of research experience has been—and will be—applied to further development of industrial and fractional horse power brushes for all types of rotating electrical equipment.

On brush operation and care—write for "Modern Pyramids" to National Carbon Company, Inc., Cleveland 1, Ohio, Dept. 15E.

★ BUY UNITED STATES WAR BONDS ★

The word "National" is a registered trade-mark of National Carbon Company, Inc.

NATIONAL CARBON COMPANY, INC.

Unit of Union Carbide and Carbon Corporation

CARBON PRODUCTS DIVISION, Cleveland 1, Ohio UCC New York, Pittsburgh, Chicago, San Francisco

KEEPING UP WITH *Electricity*

BROADCASTING TIN. "Flowing" tin plate by induction heating is now accepted practice in the industry. Frequency used in the first installation was 200,000 cycles per second—and the equipment was salvaged from a discarded broadcasting unit! Incidentally, this first installation is still in daily use.

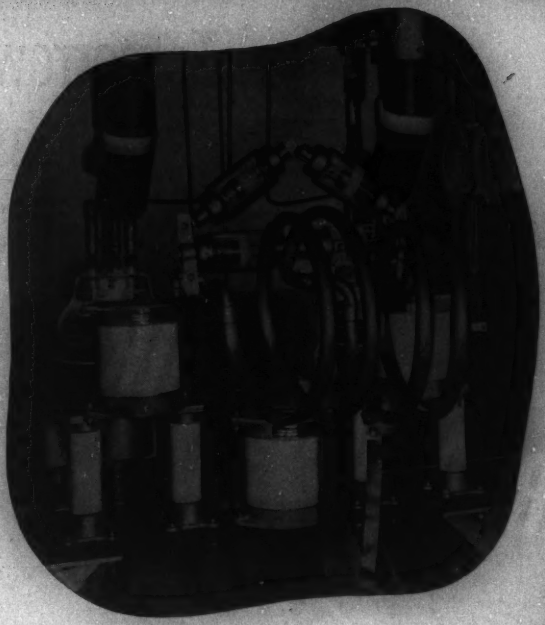
IT'S A MATTER OF SPEED. Radium gives out 1,200,000 times as much energy as the same weight of coal burned with oxygen. Even if we had plenty, however, it would probably be a poor substitute for coal, since it releases energy only one-eightieth as rapidly. Nothing that scientists have been able to do has had the slightest effect in speeding up the process.

THE SUN IS STILL SLOWER, releasing energy by a process which involves the transmutation of elements and takes between six and seven million years.

WOMAN'S WEAPON. One reason that electric irons aren't being made is that the thermostats used to control their temperature are busy on land, sea and air. They're guarding against motor trouble in tanks, fire danger in planes, overheating in gun equipment on battleships.

PEAK FLATTENERS. Resistance welders have speeded up production in thousands of war plants, but they have imposed enormous on and off single-phase loads on power circuits, often building up impossible peak demands. Capacitors are proving to be the answer, correcting the power factor to approximate unity.

THE HIGHER, THE FEWER no longer applies in radio vibrators. At high altitudes, vibrator contacts literally "boiled away" in ten hours, hence this type of radio was seldom used in airplanes. New-type vibrator, using Westinghouse-developed materials and techniques, has a life expectancy equal to that of the plane.



Plastics, plywood and electronics

This is a Westinghouse laboratory set-up for research in dielectric heating—internal heating by high-frequency radio waves. Together with induction heating—surface heating of metals by high-frequency radio waves—this process is daily finding new applications in industry.

One outstanding use of the principle of high-frequency heating is the Westinghouse development of flowing of tin on steel strip. Other important applications are in the bonding of plywood and the curing of plastics.

Dielectric and induction heating effect important savings in time and materials with attendant benefits of better control and more uniform results.

High-frequency heating is an example of electronics at work, another phase of Westinghouse leadership in electricity. Westinghouse Electric & Manufacturing Co., Pittsburgh 30, Pa.

WESTINGHOUSE PRESENTS: *John Charles Thomas, Sunday, 2:30 p.m., E.W.T., NBC. "Top of the Evening," Mon. Wed. Fri. 10:15 p.m., E.W.T., Blue Network.*

Westinghouse

PLANTS IN 25 CITIES OFFICES EVERYWHERE

THERE have been many dramatic moments when radio history was made.

One of them came four years ago...

June, 1940: The curtain slowly rises. Suddenly a spotlight flashes on, sweeps across the dark stage, picks out an unbelievably tiny radio set—less than 3 inches high, 3½ inches wide, 8⅛ inches long. Radio's newest marvel is unveiled—the "Personal Radio"—made possible because of 4 entirely new-type RCA tubes, called *Miniatures*.

War—today: A paratrooper lands behind enemy lines. Something else has arrived seconds ahead of him—dropped, as *he* was, from the sky. The tiny beam of his flashlight flicks on—probes the dark—and finds it: his victory-vital "Handie-Talkie," made possible again through *Miniature* tubes.

Tomorrow, too, the spotlight will be on Miniatures, for once Victory is won, *Miniatures* will play an increasingly important part in the many new radio and other electronic devices you designers will create.

RCA, eager to help, will gladly advise you now which Miniatures will be among the tube types most likely to be included in RCA's post-war "Preferred Type Tube" list. If you want this information, simply write to RCA, Commercial Engineering Section, 709 South 5th Street, Harrison, N. J.

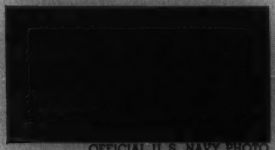
RCA

RADIO CORPORATION OF AMERICA

Tiny Electric Motors, Insulated by National, Give American War Planes the Versatility Which Builds Air Superiority!

AND NATIONAL INSULATION CAN BUILD SUPERIORITY INTO YOUR MOTOR, TOO

IF YOU BUILD, repair or maintain rotating electrical machines —from flea-power to giant size—National insulation can help you do the job better. Now!—not tomorrow, not when reconversion stares you in the face. National insulating materials are in stock, ready for you *now*. And can they really help you do the job better? Well, they're serving in the toughest kinds of installations from the heat of Pittsburgh's steel to the bitter cold of Russia's Archangel; they are used in our own coil production, and National coils are internationally known for excellence; they are formulated and produced under strict, continuous laboratory control; when you specify [redacted] insulation you specify "National," for [redacted] is a National trade-mark. If you have an especially difficult insulation task right now, tell us about it; we'll offer practical suggestions. And by all means write for our Insulating Materials Catalog No. 104. It's a mine of information.

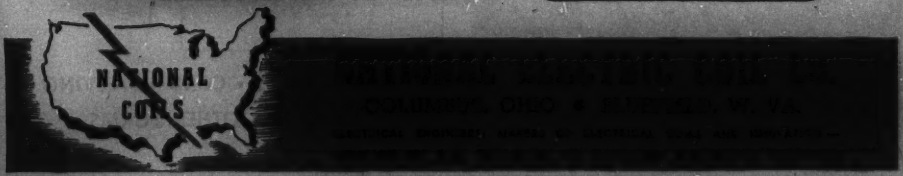


OFFICIAL U. S. NAVY PHOTO

The two tiny motors pictured above are, like thousands of others, insulated by National materials. They, or others like them, are used in every modern American fighting plane such as those on the aircraft carrier illustrated. The necessity for maximum performance demands the best — Micr-Glas.

Special Insulation Shapes Cut to Order

While insulating materials are normally furnished in sheets and rolls, they can also be supplied in special insulation shapes, accurately cut to your specifications. By a high-speed production process, and also by combining production on different orders, such shapes are very often supplied at considerably less cost than you can produce them yourself. This applies even to relatively small quantities of a specified shape. And they'll fit! Prompt action, too. Send specifications today for a quick quotation.



Fiberglas* properties

—helpful in solving problems in electrical insulation

Fiberglas is glass. It will of itself withstand temperatures far in excess of any requirements of an electrical insulation. But high heat resistance is only one of its many basic properties.

Low space factor (thinness) combined with high tensile strength make Fiberglas highly desirable in many applications in which its high-temperature characteristic has value only as a safety factor . . . In textile form, Fiberglas is available in thicknesses down to 2 mils (.0020").

Fiberglas is resistant to moisture, most acids, oils, corrosive vapors. Again, these properties make it highly desirable for electrical use where high heat resistance is important only as a safety factor.

In textile form, Fiberglas is a good conductor of heat. This property also permits its use in many electrical applications.

And, of course, Fiberglas is permanent. It does not deteriorate with age.

Treated and Untreated Forms

Untreated Fiberglas is available as cloth, tapes, sleeving, and cord.

In treated forms, Fiberglas is available as varnished cloth and tapes; combination Fiberglas-and-mica sheets and tapes; pressure-sensitive tapes; single, double, and triple saturated sleeving; varnished tubing; and laminated Fiberglas sheets, sticks, or wedges.

Fiberglas-covered magnet wire, lead wire, and other wires are obtainable from leading wire manufacturers.

Fiberglas is now available for immediate delivery. Increased production facilities make this possible. Consult your electrical distributor. *Owens-Corning Fiberglas Corporation, Toledo 1, Ohio, Fiberglas Canada, Ltd., Oshawa, Ont.*

FIBERGLAS

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ARMY E NAVY

YARNS • TAPES • CORD • SLEEVING

CLOTH and OTHER FORMS

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Your Own Trade Mark

The wires and cables you incorporate in your products must be every bit as dependable as the components you produce yourself. To back up our fighters today, and to back up your trade-mark in the peacetime battle of tomorrow, you can count on Roebling Electrical Wires and Cables. The conductors are drawn and stranded and laid with all the skill of years of wire specialization, Metal selection, insulation, finish are supervised with highest integrity.

You can put your trade-mark, without hesitation, on any electrical product you make in which Roebling Wires or Cables carry the loads.

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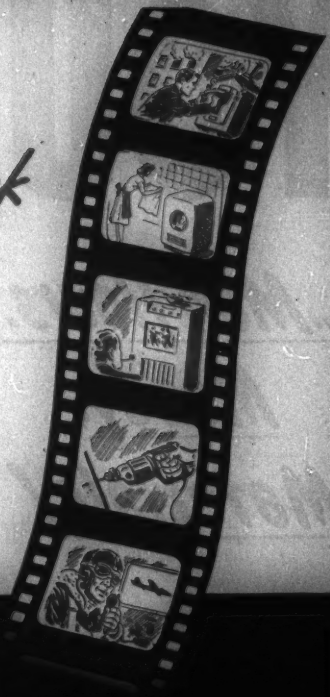

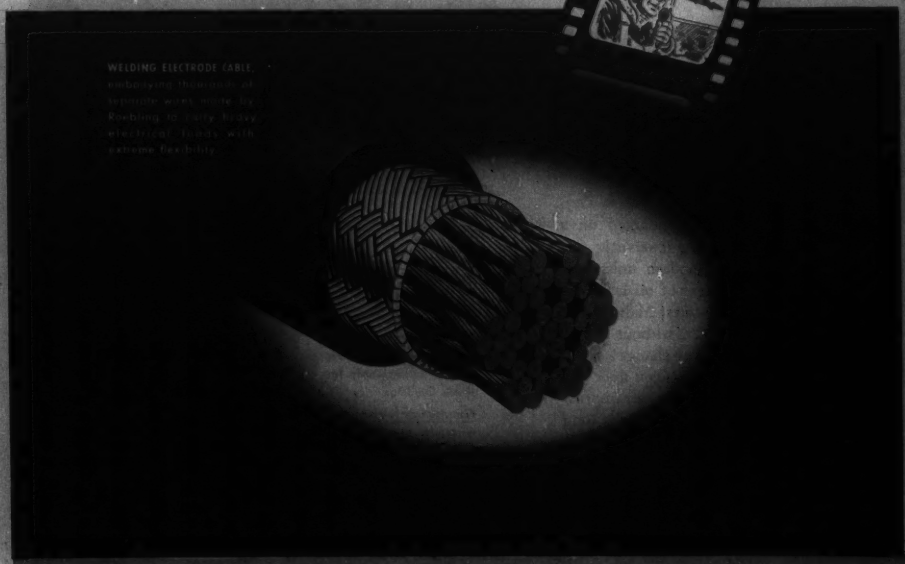

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ARCORD, SWAGED TERMINALS AND ASSEMBLIES • SUSPENSION BRIDGES AND CABLES • ELECTRICAL WIRES AND CABLES
WIRE CLOTH AND NETTING • HIGH AND LOW CARBON ACID AND BASIC OPEN HEARTH STEELS

YOU SAVE

...Man-Hours, Money, Materials!

Here's Power Where You Need It . . . an Allis-Chalmers Dry-Type Transformer Installed Right at Load Center!

THAT 25 KVA Allis-Chalmers Dry-Type Transformer is mounted on a post—*right by* the grinder it serves!

You can put these modern units *anywhere*. There's no danger of oil leaks . . . no need for fireproof vaults! Maintenance is no problem either . . . without insulating liquid to test, filter or change!

Load center location gives you finer voltage regulation, lower line losses, improved motor performance—cuts need for long runs of secondary copper!

Allis-Chalmers Dry-Type Transformers are available for quick delivery . . . *now!* Get the full story from our nearby district office. Or write, ALLIS-CHALMERS, MILWAUKEE 1, WISCONSIN. A 1693

CHECK THESE TRANSFORMER FEATURES:

Smaller, Adaptable Size — permitting quick, easy changeover.

Easy-To-Get-At connections and knockouts; fast installation.

Windings Separated by solid insulation — meet safety requirements for inside buildings.

Coils Heavily Impregnated — rendering windings resistant to moisture.

Wide Range of Sizes — 1½ to 500 kva, single and 3-phase, with incoming voltages up to 15,000 v.

ALLIS-CHALMERS

Illustration shows S & C Load Interrupter Disconnects and Type "SM" Fuse installations. Disconnects closed at left and open at right.

Load Switched to Load Centers from Either of Two Sources

TO be sure of continuous service for this essential war plant,—the substation is supplied from two service cables.

To switch to either of these feeders, S & C Load Interrupter Disconnects are installed,—the *only* open type Interrupter Disconnects suitable for outdoor load switching of this kind.

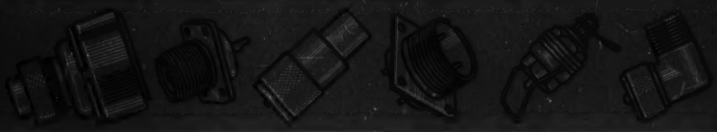
Besides load switching operations short-circuit protection is provided by S & C type "SM" Fuses on the same mounting base.

With S & C Load Interrupter Disconnects, load currents up to 400 amperes at 15000 volts can be interrupted—*without arcing at main switch contacts.* Substantial initial and maintenance savings are effected. Space, weight and installation time are reduced.

Consult S & C engineers the next time you have a job of this kind.

S & C

When You Think



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ELECTRICAL ENGINEERING

Registered United States Patent Office

MAY

1944

The Cover: Lookouts on this South Pacific transport communicate with the bridge by telephone; this is just one of numerous vital functions performed electrically on modern ships (pages 170–4).
United States Navy photo

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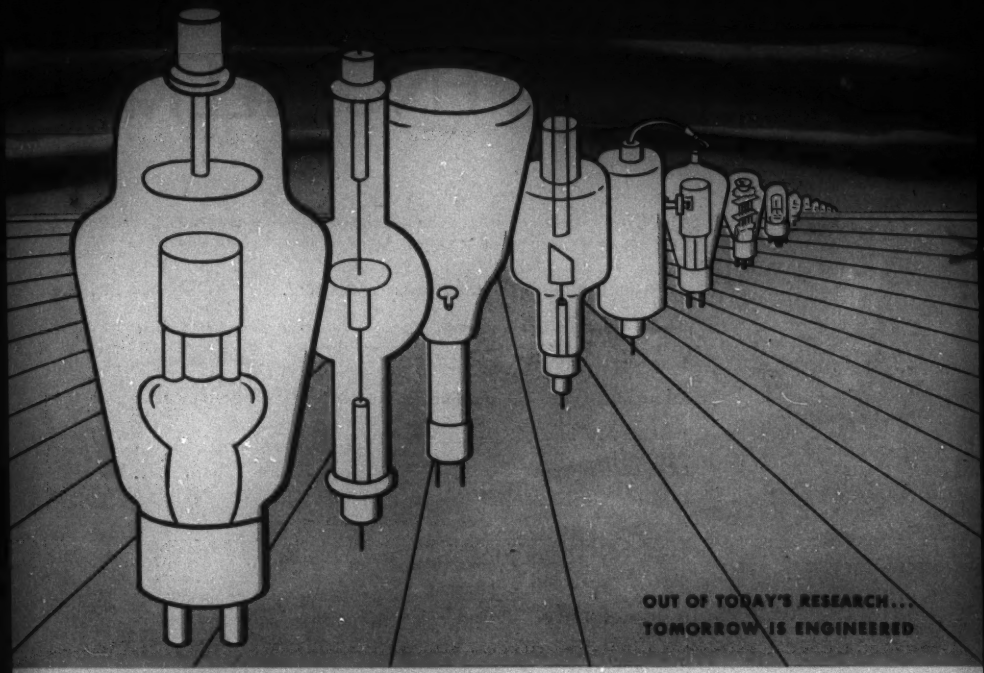

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AlSiMag Steatite Ceramic Insulators are non-inflammable. As they do not contain carbon, they do not char. Electrically conducting paths are not formed as a result of arc over or other heating.

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Mechanical strength is exceptionally high compared with ceramics in general or with organic materials.

AlSiMag Steatite Ceramic Insulators have exceptionally Low Loss Factor, High Dielectric Strength and High Resistivity.

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ARMY E NAVY

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STEATITE CERAMIC INSULATORS

Electrical Engineering in the Postwar World

I—Influence of Wartime Developments

NEVIN E. FUNK
PRESIDENT AIEE 1943–44

Engineers have been devoting and will continue to devote first attention to winning the war—the problem that stands paramount to all others today; but as the peace to follow promises to be still more highly technological than even this war has proved to be, it is imperative that engineers have an eye to the postwar world. Likewise, "Electrical Engineering," which has been devoting and will continue to devote primary attention to war problems, now should look also to the postwar period. Therefore, a series of articles on the general topic "Electrical Engineering in the Postwar World" is being developed for serial publication. It is hoped that these articles, which are being prepared by prominent electrical engineers, will prove stimulating and thought-provoking, and that they thereby may make some contribution toward winning the peace. President Funk sounds the keynote of the series in this introductory article. Succeeding articles will cover various phases of the subject. Additional comments from readers are invited. —Editors

IT IS not the purpose of this article to deal with any specific branch of electrical engineering or science, nor to present a detailed discussion of types of improvement in equipment design, since these various fields of activity will be covered adequately by specialists in later articles in this series. Rather I wish to draw a general picture of what we may hope will happen in the future.

As we unroll the scroll of history, we find that age after age nations rose to great heights of civilization, and then declined and finally perished in the disaster of war brought on them by enemies who had not been softened by easy living, and who had developed new implements of war to give themselves greater assurance of victory. The earliest wars covered only a very small portion of the earth. However, with the development of newer means of transportation, the area involved in conflict increased in each succeeding major war. As increasingly greater forces were involved, each side, with newly acquired technical knowledge, developed mechanical implements of destruction to support the efforts of its individual soldier. These new mechanical devices were intended to give each soldier the advantage over his adversary and thus multiply the effectiveness of the fighting personnel.

In each case, after the struggle had ceased, lessons which were learned through efforts to improve the fighting mechanization were applied to the pursuits of reconstruction and the furtherance of peaceful endeavors. World transportation continued to improve both in convenience and in speed. However, instead of bringing to greater sections of the world a more intimate appreciation of each other, this improvement in transportation seems to have resulted only in broadening the area involved in the conflagration of war until today the populations of practically the entire world are at each other's throats.

In an endeavor to win in the present conflict, our science and engineering, working hand in hand with industry, have developed, produced, and put in the fighting field implements of war undreamed of a few years ago. These devices now make it possible to reach behind the fighting forces and blot out the sources of supply—in effect, to put the entire civilian population in the front-line trenches. The question of whether or not knowledge of these new developments will make the nations realize that modern warfare is so destructive that even the victor losses cannot be answered at this time. However, the application to peaceful pursuits of these many developments which were only in the embryo stage at the beginning of hostilities certainly will be accelerated after the war.

Although throughout history each succeeding war has been more mechanized than the preceding ones, the present conflict surpasses by far in every department of warfare anything that has gone before. The chief reason for this is the tremendous strides that have been made in the knowledge of science and its application in the past two decades, knowledge which could be turned immediately into the channels of fighting materials. Conversely, the intense devotion of every effort toward the production of still better weapons will have built up at the end of hostilities a vast storehouse of perfected mechanisms ready to be adapted to peaceful pursuits. It is to be expected that greater advances will be made in engineering progress at that time than have ever been seen before.

Nevin E. Funk is vice-president in charge of engineering, Philadelphia Electric Company, Philadelphia, Pa.

During the Civil War in the United States electricity played a part in military operations for the first time, and then only to a small extent in communication, since the telegraph was the only practical electric device available. However, in each succeeding war the use of electricity has increased, until now there is scarcely any device used, the satisfactory functioning and control of which does not depend in some way upon the application of electrical science. The war needs of the moment have speeded up electrical developments; when these developments are applied later to civilian uses, they will not only make material changes within the electrical industry itself, but also affect many manufacturing processes—in some cases almost to a revolutionary extent—and leave their mark on the products of most industries.

When we consider the changes taking place in electrical engineering, we must realize that practically all types of engineering science are inherently interrelated and interdependent in our present economy. Change in one is bound to reflect to a greater or less extent in some or all of the others, depending on its nature. We also must keep in mind that in our use of electricity we rely more on its manifestations in the form of light, heat, mechanical power, and chemical effects, than we do on some of its other characteristics. As an illustration of the postwar trend, a few examples of what may be expected in electrical developments after the war are cited in this article. These, however, must not be considered as in any way circumscribing the potential postwar field of electrical engineering.

Progress has been made in aviation which was undreamed of a few years ago. In this progress electrical engineering has played no small part, not only in providing greater safety in the ability to control planes, but in developing a type of communication which was only hoped for a few years ago. The new knowledge gained in these developments will not only increase materially the safety of air travel in the future, but make it less dependent upon weather conditions.

In all probability much of the equipment developed for the guidance of airplanes can be adapted to increase the safety of ships at sea. Such equipment might also be used to safeguard train operation by keeping the locomotive engineers of the future in continuous contact with the train dispatching office of the railroads. Furthermore, it is not at all impossible that we may find long-distance wire communication supplemented where required, by radio telephony.

Lighter-weight equipment for power purposes, capable of operating at frequencies ranging from 400 to 500 cycles, and lighter-weight higher-speed generators and motors have been built for use in the field of aviation. The experience and knowledge gained in this entirely new field of design in all likelihood will find their way into many civilian uses, although probably not as direct applications of the equipment as developed.

Materials can now be welded successfully which previously were not responsive to this type of operation. Entirely new electric-welding tools and automatic welding devices have been developed, which would have been very slow in making their appearance but for the tremendous mass production that came with the war. As a matter of fact, electric welding is used in the production of practically every implement of war. Because of the urgency of the present situation, welding operations have been attempted and have turned out successfully which under normal conditions probably would have been rejected at the outset as impractical.

Drying with infrared light rays had been applied successfully in a few instances previous to the war. This new development has been promoted materially by the present need for increased production and the necessity of reducing the time involved in operation. It is to be expected that after the war a radical change will be made in method by almost every industry concerned with the quick drying of paints, enamels, and varnishes. Many other applications of this type of heating probably will be made outside of this field.

An entirely new type of heating has been developed during the war, namely, electronic heating. This has been used to speed up the drying of glues used in building up the laminations of plywood. Its speed of drying and increased adhesion, compared with the old methods, are really miraculous. This type of heating is only in its infancy.

Although we had short-duration high-intensity lighting to make photographs of high-speed motion previous to the war, now even shorter-duration light of still greater intensity is available. This development permits the analytical study of very high-speed motions which previously could not be made. Its use will increase materially the basic knowledge of high-speed mechanisms of this type, as well as open up the possibility of producing entirely new designs. Along with this light for study of high speed has come high-speed X ray which will add materially to our knowledge.

We have made tremendous steps in the mass production of many items which we formerly thought could not be produced by this method. In applying these lessons later to our civilian economy, we should be able to manufacture many articles more cheaply than we previously knew how, and thus make them available to many more consumers. This unquestionably will apply to articles in popular demand as well as to the more technical types of equipment.

There undoubtedly will be some revolutionary developments in the application of plastics to the production of electrical equipment, not only as an insulating material, but in some cases replacing metal as the main framework of the device. Plastic affords a pleasing and lasting finish inherent in the material itself and has the additional desirable feature of reduced weight.

Because of the astounding results obtained from their application, electronic devices have appeared to the popular mind to be the major electrical improvements which have come out of the war effort. Although it is true that increased application of electronic devices is the most spectacular development, many far-reaching changes have been made also in the design of normal types of equipment which ultimately will result in the improvement of almost everything electrical.

There has been practically a cessation in the production of any but the most necessary equipment for civilian use. However, even though their present efforts are applied wholly to war production, the men who formerly manufactured products for civilian use cannot help but consider occasionally the possibilities of what can be done to improve their prewar products when they can start manufacturing them again. Without question their ideas have been changed by the new types of work they are now doing, and, if in the past they had gotten into a groove, these war

years will have started them along new lines of thought which are sure to bring about many new improvements.

Although it is too early to make any predictions concerning the trend that the improvements in the distribution of electric energy will take, nevertheless, I am sure that we will find application for new ideas which have been brought out in vastly different lines of endeavor. Already there seem to be some possibilities in the application of new electronic developments for relaying, remote control of switching, and telemetering. Although the work on the distribution system has been almost at a standstill, because materials were not available, and extensions and improvements necessarily were curtailed so that essential materials could be used in war work, nevertheless, many distribution engineers have been giving serious thought to what can be done when normal conditions return.

We must not overlook the fact that the present fighting personnel has been more highly trained in the handling of highly technical intricate equipment in this war than in any before. These men on coming home will enter all types of industry and will bring a fresh point of view, new ideas, and a zest for applying these ideas to normal living.

But with all the new technique we have gained, with the many almost astounding developments which have arisen, our major postwar asset still is the pioneer spirit existing in the minds of men—their firm determination to regain ground lost because of the war and to progress along the road to better living.

The Combustion Gas Turbine

F. K. FISCHER C. A. MEYER

THERE ARE many conceivable future uses of the gas turbine, because it potentially promises higher efficiency at very high temperatures than most engines and prime movers used today. Future applications range from electric-power generation to power plants for propelling airplanes, trains, and ships.

Advantages of the gas-turbine cycle as compared to the conventional steam system include the following: (1) no boiler is used; (2) water is not required for the simple open-cycle system; (3) it promises greater efficiency improvement at high temperature; and (4) it offers high horsepower-per-pound output for short-life applications. Factors which may retard its development include (1) the overoptimism of its potential users concerning its possibilities; (2) the necessity of using high-grade oils for fuel instead of low-grade oils and coal; (3) insufficient field experience with the gas-turbine cycle; and (4) the need for time to complete technical developments in metallurgy and component parts of the gas-turbine system. To a considerable degree, the future application of the gas turbine depends upon developments in the fields of metallurgy, aerodynamics, combustion, and heat exchange. Present knowledge in these fields permits building and operating simple gas turbines for certain purposes. Experience with some of the simple forms of gas-turbine plants has been successful and encouraging. In the postwar period, industry will benefit from the developments now being engineered for war. These developments will accelerate the application of gas-turbine plants to new and larger fields.

Engineers have been experimenting with the combustion-gas-turbine cycle for many years. Although present uses of the gas turbine are limited by the necessity of relatively high-grade fuel oils and materials that will withstand very high temperatures, research now being conducted for the war program may change the status of the gas turbine considerably in the postwar era.

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GAS TURBINE IS SIMPLE

The fundamental directness of the gas-turbine power cycle, in which all the hot gases of combustion are led straight to the turbine, has intrigued engineers for years. Versatile Leonardo da Vinci devised a crude version. In 1791, John Barber, an Englishman, took out the first patent on a turbine operated by gases. Since then there has been an almost continuous stream of developments.

Progress toward a practical gas-turbine power unit has been delayed because the thermal efficiency required to make it competitive with the highly developed steam cycle required:

1. Operation above 1,000 degrees Fahrenheit.
2. A highly efficient compressor.
3. A highly efficient turbine.

Two seemingly unrelated industries recently have made important contributions to help solve these problems. Metallurgists, in developing materials for superchargers, have produced alloys that are expected to withstand at least 1,200 degrees Fahrenheit in continuous service at the low operating pressures encountered in gas-turbine work. Aviation and wind-tunnel research on airplane wings has contributed fundamental aerodynamic data on which high-efficiency compressor designs are based. The research in these two industries plus the accumulated steam experience of many years has made possible the necessary high-efficiency turbine and compressor elements and has solved many of the mechanical problems involved in gas turbines.

In the combustion-gas-turbine system of power generation there are two basic cycles—the open cycle for moderate capacities and the closed cycle for very large units.

The open-cycle combustion gas turbine provides power directly to drive generators or machinery, since in its power cycle all the hot gases of combustion go straight to the turbine, and thus the necessity of the steam boiler, a big and expensive item, is eliminated. By contrast, in the highly developed steam cycle, the fuel energy must be converted to steam before expending its energy in the turbine.

HOW CYCLE WORKS

The combustion-gas-turbine cycle in its basic form employs the simplest power cycle known, comprising only three major elements: compressor, "combustor," and gas turbine; plus a generator or shaft for transmitting the useful power output, and a means of starting. This simple arrangement is called the open-cycle system. A general idea of the appearance and relative size of the major elements is given in Figure 1. The gas turbine resembles the straight-reaction noncondensing steam turbine. Gas-turbine blades look more like air-foil sections than reaction steam-turbine blades because of the small pressure drop and large gas volume involved. The axial-flow compressor also resembles a straight-reaction turbine, with the gas to be compressed passing axially through the compressor. The action of the blades in the axial-flow compressor is the reverse of the action of expansion in a reaction turbine. This physically small compressor handles the large volume of gas efficiently. The combustor is the burner in which

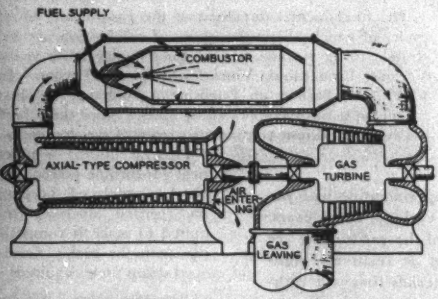

Figure 1. Elements of gas-turbine cycle are: a compressor, a combustor, and a gas turbine

the chemical energy of the fuel oil is converted into heat energy by burning the fuel with sufficient excess air to obtain the desired temperature. The hot product of combustion from the combustor is the gas, which, expanding to a lower pressure and temperature in the gas turbine, converts some of its heat energy into mechanical energy at the turbine shaft. The combustor is relatively small, since its rate of heat release is many times that of the conventional steam boiler which, in addition to burning fuel, must transfer the heat through tube walls to generate steam.

To start a combustion gas turbine some external means, such as a motor, is required, since the air for combustion is supplied to the combustor by the compressor. When the unit is in operation, the energy to drive the compressor comes from the expansion of the products of combustion in the gas turbine.

In the simple cycle operating at 1,200 degrees Fahrenheit, the products of combustion (gas) contain some 600 per cent excess air. This gas is expanded in the turbine and exhausted to the atmosphere. No intermediate fluid is used as in the steam cycle, where fuel is burned and releases chemical energy as hot products of combustion which pass through a steam boiler to generate steam for the steam turbine. The steam generator, or boiler, is the biggest single element in the steam power plant. In the gas cycle a compressor and combustor replace the boiler, and this results in a much smaller and more compact power plant. Because the simple open combustion gas cycle does not require cooling water, no steam condenser such as that used in the condensing steam cycle is needed, and plants may be located without regard to a suitable source of cooling water.

Although the first patent was taken out over 150 years ago, early inventers were unsuccessful in getting units efficient enough to drive their own compressor. The cycle was perfectly sound, but, these early inventers lacked both

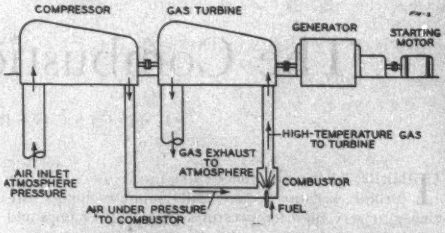

Figure 2. Simple open cycle of combustion gas turbine

materials to withstand the necessary high temperature and turbines and compressors of suitable efficiency.

HIGH-TEMPERATURE METALS DEVELOPED

Today the story is changing. Materials have been developed that are capable of operating at high temperatures. The maximum temperature employed in a gas-turbine cycle now is dependent largely on the required length of useful life of the apparatus. For a life of relatively few hours, such as might be satisfactory for some military needs, temperatures of the order of 2,000 degrees Fahrenheit are allowable. Heavy-duty long-life applications are limited to much lower temperatures. The tremendous advances made in metallurgy for the war effort, undoubtedly will produce materials capable of operation at temperatures which we would not have attained for many years under a normal peacetime development.

The combustion gas turbine requires tremendous volumes of gas. The axial-flow compressor, small in physical size, efficiently handles the large volumes required. Until recently the axial-flow compressor was to a considerable extent an unknown quantity. Today, the advancement in knowledge of proper blade shapes and research in the development of efficient air-foil sections have given the designer the necessary tools to design and build highly efficient axial-flow compressors.

TURBINE AND COMPRESSOR EFFICIENCY IS BIG FACTOR

In the gas-turbine cycle, the useful power output depends upon obtaining relatively high turbine and compressor efficiency. The useful net output is the difference be-

tween two fairly large quantities: the total turbine output and the work consumed by the compressor in compressing the air. With the system of Figure 2 operating at a top temperature of 1,200 degrees Fahrenheit, for each useful unit of power output, the turbine develops 3.95 units, of which 2.95 is needed to drive the compressor. A reduction of one per cent in the efficiency of each of these elements reduces the useful output by seven per cent. The useful output decreases sharply as the top temperature is lowered.

In Figure 3 the simple gas-cycle thermal efficiency is plotted as a function of the pressure ratio for several turbine-inlet temperatures of the combustion gas. Pressure

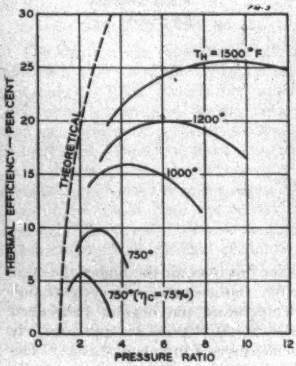

Figure 3. Effect of pressure ratio on thermal efficiency of open-cycle gas turbine without reheat, intercool, or regeneration

Assumed efficiencies: turbine 85 per cent, compressor 84 per cent, combustor 100 per cent. Air temperature 70 degrees Fahrenheit

ratio is the compressor discharge pressure divided by the compressor inlet pressure, which is 14.7 pounds per square inch absolute in the open cycle. The curves are based on these efficiencies:

Turbine—85 per cent.

Compressor—84 per cent.

Combustor—100 per cent.

Air-inlet temperature—70 degrees Fahrenheit.

The 750-degree-Fahrenheit curve is plotted for two different compressor efficiencies showing the effect of change in efficiency of one of the elements. A reduction in compressor efficiency of nine per cent cuts the cycle efficiency almost in half. The relatively low pressure ratios at which maximum efficiency is obtained, around 6 for 1,200 degrees Fahrenheit, means that relatively low turbine-inlet pressures exist in the open cycle, under 100 pounds per square inch absolute. Low pressure results in large gas volume and relatively large turbine-blade dimensions.

Engineers have been experimenting with this combustion-gas cycle for many years. In Europe, because of economic conditions engineers attempted to develop it as soon as materials and compressors even remotely offered a possibility of building successful units. In the United States, much of the recent development has not been described in published material because of present Government prohibition in the interest of security. However, the literature contains a considerable description of prewar applications in Europe. These plants are inferior in efficiency to what can be built today, but they apparently are giving satisfactory results. Interesting applications include a turbine locomotive, electric-generating set, compressor drive for Velox boiler, refinery drives, and airplane propulsion.

REGENERATING, INTERCOOLING, AND REHEATING AID EFFICIENCY

As shown in Figure 3 the efficiency of the simple open gas cycle is low unless extremely high temperatures are used. However, there are three practical ways of improving greatly the gas-cycle efficiency. They are: regenerating, intercooling, and reheating. The regenerating gas cycle

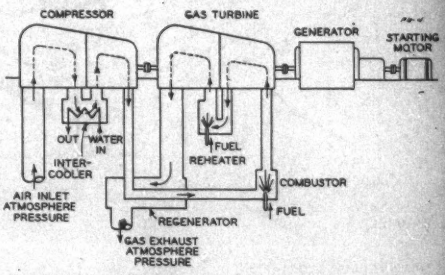

Figure 4. Intercool, reheat, and regeneration for open cycle

is a cycle in which a heat exchanger (regenerator) transfers some of the heat from the relatively hot exhaust gases leaving the turbine to the air before it enters the combustor. Heating the air by exhaust gases reduces fuel consumption and improves the cycle efficiency. The amount of heat obtained from the exhaust gas depends on the size of the heat exchanger. This is an economic problem in which gain in efficiency is balanced against cost of heat-exchanger surface. Calculations indicate that the economic size of the heat exchanger will limit the regenerating cycle, at 1,200 degrees Fahrenheit inlet temperature, to approximately 75 per cent recovery of the heat available from the turbine exhaust gases. This economic size will be about 0.30 cubic foot of heat-exchanger volume per kilowatt of capacity.

Efficiency is improved further when intercooling is added to regeneration. As the name implies, intercooling removes the heat of compression from the air passing through the compressor. Water, circulating through the intercooler, cools the air and is a necessary part of the cycle. By intercooling, the compressor work is reduced, because the colder air has smaller volume. Other conditions remaining the same, one stage of intercooling will reduce the compressor work by some 15 per cent. This increases the portion of the turbine capacity available as useful output and improves the cycle efficiency. A large number of intercoolers is ideal, but probably only a few stages will be practical.

Reheating, the third method of improving efficiency, consists of adding heat to the gas as it passes through the turbine. Although the gas-turbine reheat cycle employs the same principle as the reheat cycle used in many steam plants, in practice it bears little resemblance to it. Reheating in the gas turbine consists of burning fuel directly in the gas (approximately 85 per cent air) passing through the turbine. The quantity of large steam piping and con-

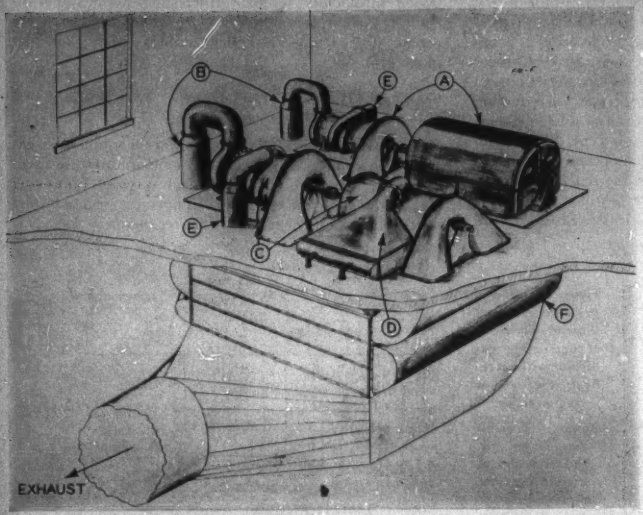

Figure 5. Artist's conception of a 5,000-kw open-cycle gas-turbine plant, using reheat, intercool, and regeneration

Two gas turbines are used: one a constant-speed generator drive, the second a variable-speed compressor drive

A—Constant-speed gas turbine and generator

B—Combustors

C—Variable-speed gas turbine and compressor

D—Intercooler

E—Reheater combustor

F—Regenerator

siderable heat-transfer surface in the heat exchanger of the steam reheat cycle is replaced by a reheating combustor which may possibly be placed inside the gas-turbine casing proper. Here again, the practical number of reheats is limited.

Reheating and intercooling increase the amount of useful energy per pound of working gas passing through the system and thus reduce the number of pounds of working medium circulated. Therefore, the size of piping and blade path in the compressor and turbine are reduced. If reheating and intercooling are used in combination with a regenerator, the terminal difference across the heat exchanger is greater for a given-size exchanger than without a regenerator, or a smaller heat exchanger transfers the same amount of heat as the larger-size exchanger. In partial-load operation the efficiency is increased by a considerable amount with this combination.

VARIOUS CYCLE COMBINATIONS COMPARED

The combination of regenerating, reheating, and intercooling is shown in Figure 4. Different cycle arrangements are compared in Table I on the basis of the power requirements of each major element, with the capacity of the generator as unity.

The thermal efficiency of the open-cycle gas turbine for various combinations of regenerating, reheating, and intercooling is shown in Figure 6. This gives the relative value of these modifications and a general idea of possible applications of this cycle. The temperature range of 1,000 to 1,500 degrees Fahrenheit was chosen, because applications at temperatures much below 1,000 degrees undoubtedly will be impractical. Early applications for heavy-duty long-life apparatus probably will not exceed temperatures of 1,200 degrees Fahrenheit with 1,500 degrees Fahrenheit and higher limits awaiting future developments in metallurgy.

The temperature of the inlet air to the compressor has a marked effect on the cycle efficiency. In contrast to steam plants, the colder this inlet air the higher the cycle efficiency and capacity. In the simple open cycle, changing the inlet air temperature ten degrees Fahrenheit changes the cycle efficiency 0.74 point or approximately three per cent per ten degrees Fahrenheit change. The effect on capacity is approximately four per cent per ten degrees Fahrenheit change. The effect on cycle thermal efficiency of inlet air temperature, on the different cycle arrangements with a top temperature of 1,200 degrees Fahrenheit, is plotted in Figure 7.

Table I. Effect of Different Open-Cycle Arrangements on Each Major Element

Item	Simple Cycle	Cycle With Regeneration	Intercool and Regeneration	Reheat and Regeneration	Intercool, Reheat, Regeneration
Input in fuel	4.95	3.75	3.43	3.55	3.11
Turbine rating	3.95	2.95	2.80	2.88	2.55
Compressor power	2.95	1.95	1.80	1.88	1.55
Useful output	1.00	1.00	1.00	1.00	1.00
Per cent efficiency at 1,200 F	20.2	26.6	29.2	28.1	32.2
Gas temperature in degrees Fahrenheit at:					
Turbine inlet	1,200	1,200	1,200	1,200	1,200
Leaving reheater				1,200	1,200
Turbine exhaust	635	790	695	920	865
Leaving regenerator		450	350	560	520
Air temperature in degrees Fahrenheit at:					
Compressor inlet	70	70	70	70	70
Leaving intercooler			70		
Leaving compressor	490	340	230	440	405
Entering combustor	490	680	575	800	750
Pressure (pounds per square inch absolute) at:					
Compressor inlet	14.7	14.7	14.7	14.7	14.7
Compressor discharge	88.2	51.5	73.5	73.5	102.9
Turbine inlet	88.2	50.2	71.7	71.7	100.4
Turbine exhaust	14.7	15.1	15.1	15.1	15.1

STEAM AND COMBUSTION-GAS CYCLES COMPARED

Because steam is the most widely used medium for transferring heat into mechanical energy, a comparison of the steam cycle and the gas cycle may help in judging the gas cycle and its possibilities. In judging the efficiency of

power cycles, a 100 per cent thermal efficiency is not obtainable, as the temperature of the cold body is far above the absolute zero of temperature. The Carnot cycle is a theoretically perfect cycle, and no other cycle operating between the same hot and cold body temperatures can have a thermal efficiency better than it. The best any cycle can hope to do, when operating under the same conditions as the Carnot cycle, is to attain the Carnot-cycle efficiency. The gas-turbine cycle theoretically can give the same efficiency as the Carnot cycle, but this is possible only theoretically, since it requires 100 per cent efficiency of the gas turbine and compressor, and infinite number of stages of intercooling and reheating, and a regenerator infinite in size.

GAS CYCLE HOLDS BEST PROMISE

The steam cycle theoretically offers the Carnot-cycle efficiency only up to the critical pressure (705.4 degrees Fahrenheit; 3,206 pounds per square inch absolute). Above this temperature, the gap between the steam cycle and the ideal cycle gradually widens as the temperature is increased. Therefore, from a purely theoretical standpoint the combustion-gas-turbine cycle holds forth greater promise of efficiency than the steam cycle.

Of more value than theoretical efficiencies are the thermal efficiencies obtainable in practical applications. Figure 8 compares the best efficiencies obtained in large central power plants (projected to 2,000 degrees Fahrenheit) with the expected practical limit in efficiency of the large-capacity closed-cycle combustion-gas-turbine power plants. Above, 1,000 degrees Fahrenheit the gas-cycle efficiency increases approximately three times as fast as the steam-cycle efficiency for a given top temperature increase.

Table II. Comparison of Combustion Gas Turbine and Steam Turbine

5,000-Kw Rating—3,600 Rpm

Item	Open-Cycle Gas Turbine			Steam Turbine—3 Stages Feed-Water Heating
		One Reheat, One Intercool, and Regeneration		
	Simple Cycle, Single Cylinder	High-Pressure Turbine	Low-Pressure Turbine	Single Cylinder
Inlet pressure—pounds per square inch absolute	88.2	100.4	39.4	465
Inlet temperature—degrees Fahrenheit total temperature	1,200	1,200	1,200	825
Exhaust pressure—pounds per square inch absolute	14.7	39.4	15.1	1½
Steam or gas rate—pounds per kilowatt-hour	102	56		10.5
Full load flow—pounds per hour	510,000	280,000		52,500
Inlet volume flow—cubic feet per second	990	475		24.8
Exhaust volume flow—cubic feet per second	3,900	3,250		6,120
Ratio of exhaust volume ÷ inlet volume	3.95	6.85		250
Turbine floor area—square feet	160	150	155	100
Net generator output—kilowatts	5,000	5,000		5,000
Approximate plant thermal efficiency—per cent	18.4*	29.4*		23.6

* Inlet air temperature 70 F.

This curve compares the best modern large central steam power plants with the best practical efficiencies expected of the combustion-gas-turbine power plants. It is expected that the gas-turbine-cycle efficiency will not be affected greatly by unit size, and this combustion-gas-cycle curve can also be interpreted as applying to open-cycle gas-turbine power plants of relatively small capacity. Economic steam plants for capacities around 5,000 kw seldom exceed 25 per cent over-all thermal efficiency. This would indicate a considerable efficiency advantage, in small units, in favor of the gas cycle, provided economics permits designing it for anywhere near its maximum possible efficiency.

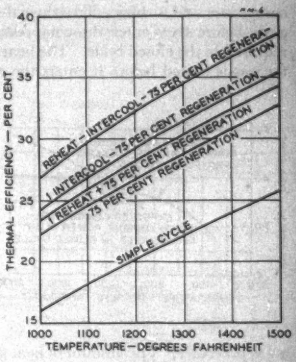

Figure 6. Effect of reheat, intercool, and regeneration on thermal efficiency over range 1,000 to 1,500 degrees Fahrenheit

Based on 70 degrees Fahrenheit and 5 per cent pressure drop in regenerator. Assumed efficiencies: turbine 85 per cent; compressor 84 per cent; combustor 100 per cent

Table II, which compares a 3,600-rpm 5,000-kw steam turbine with a 3,600-rpm 5,000-kw net-output open-cycle gas turbine, shows the low pressure in the open-cycle gas turbine as contrasted to the high pressure in the steam cycle. The energy per pound of gas is small, and the flow of gas is very large: 510,000 pounds per hour for the simple-cycle gas turbine as compared to 52,500 pounds per hour of steam to the steam turbine. The large flow and low pressure to the inlet of the gas turbine gives a large volume flow which means that the piping and blading of the gas-turbine inlet are large compared to that of the steam turbine.

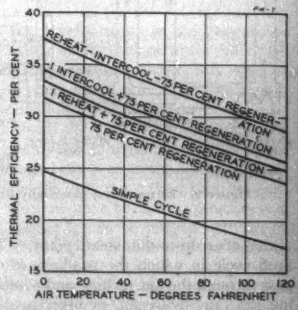

Figure 7. Effect of air temperature on thermal efficiency of open-cycle gas turbine with 1,200 degrees Fahrenheit inlet gas temperature

Efficiencies, air temperature, and regenerator pressure drop same as in Figure 6

The ratio of exhaust to inlet volume is small for the gas turbine. This makes a balanced blade path unlike that of the steam turbine, which in this case must handle an exhaust volume 250 times as great as the inlet volume. The large blade dimensions limit the maximum net-output rating of the open-cycle single-flow combustion gas turbine to approximately 7,500 kw. However, the injection of liquids offers a theoretical possibility which extends this limit considerably.

CLOSED CYCLE FOR LARGE UNITS

The closed cycle offers a method of increasing the maximum capacity of the open cycle. The volume of the working gas is inversely proportional to the absolute pressure. If the pressure is multiplied by 10, the size is divided by 10. In the closed cycle, the circulating working gas is at a relatively high pressure and reduces the physical size of compressor and turbine. To reduce the temperature of the gases before they enter the compressor, cooling water is required in the closed cycle. The heat exchanger in which the gas is cooled before it enters the compressor is called

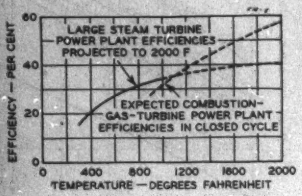

Figure 8. Efficiencies compared for best practical steam power plants and combustion-gas-turbine plants

a gas precooler. The amount of heat given up to the cooling water is equivalent to that removed in the condenser of a steam unit of equal capacity. The quantity of cooling water required will be less in the gas unit than in the steam unit, as a higher water temperature rise is permissible in the gas unit.

The closed cycle in Figure 9 is the one used by Escher Wyss, a Swiss firm who claim that it has an efficiency equal

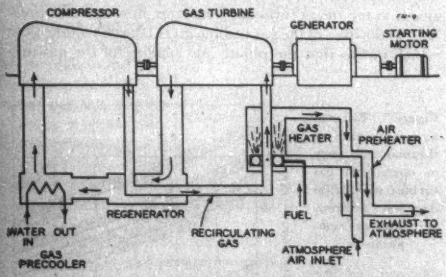

Figure 9. Escher Wyss externally fired closed cycle

to that of an up-to-date steam plant.[4] This is an externally fired cycle in which the products of combustion do not pass through the gas turbine and compressor. The working gas (air, hydrogen, or other medium) operates at a relatively high pressure in a closed recirculating circuit. In the gas heater, the heat from the products of combustion is transferred to the working gas which then expands in the turbine to a lower pressure. The gas heater in this cycle corresponds to the steam boiler in the steam cycle. For a practical efficiency, it will be larger than the modern steam boiler, because gases are on both sides of the gas heater. This cycle is very similar to the steam cycle, except that the working fluid does not undergo a change of state. As this closed cycle keeps the products of combustion out of the turbine and compressor circuit, the problem of using coal as a fuel should be much simpler of solution than in those cycles which circulate the products of combustion.

HYDROGEN HAS ADVANTAGES

In the closed cycle, the compressor inlet pressure will be maintained at approximately 150 pounds per square inch with a discharge pressure of some 600 pounds per square inch. This high pressure greatly reduces the size of turbine and compressor and should permit maximum ratings to be built approaching those in the steam cycle. Some gas other than air may be used as the working medium in the externally fired closed cycle. Hydrogen, for example, has properties which make it far superior to air for this application. The density of hydrogen is $^1/_{14}$ that of air, the specific heat is 14 times that of air, and the thermal conductivity is 6.8 times that of air.

NEW CYCLE STUDIED

A closed-cycle system under development by Westinghouse Electric and Manufacturing Company is shown in Figure 10. In this closed cycle a separate gas turbine and compressor are used to pump up the cycle on which the main gas turbine and compressor operate. High pressure of around 600 pounds per square inch may be used with a compressor inlet pressure of around 150 pounds per square inch. The main gas turbine and compressor would be small as they operate at high pressure. This cycle is fired internally, the products of combustion passing through the gas turbines and main compressor. A compressor driven by a second gas turbine supplies enough make-up air to maintain pressure and support combustion. This closed cycle eliminates the necessity of the large gas heater required by the Escher Wyss cycle, but requires an extra gas turbine and compressor to pump up the system. Solid matter from the fuel must be removed.

In the closed cycles shown in Figures 9 and 10, reheating and intercooling are not illustrated. However, they offer the same advantage in the closed cycle that they offer in the open cycle. The biggest single additional problem in the closed cycle is a method of building practical heat exchangers. The problem is complicated further by the fact that the gases will carry foreign matter from combustion which may both corrode and erode the exchanger and reduce the heat-transfer rate by depositing foreign material on the transfer surface.

GAS-TURBINE CONTROL

Combustion-gas-turbine control can be simple and reliable, consisting only of regulating the gas temperature by controlling the rate of fuel supply. Governing valves, such as those used in steam-turbine control, are not needed. Efficient partial-load performance can be obtained by using two turbines: one variable-speed turbine driving a compressor; plus a constant-speed turbine driving a generator. The use of regenerators, reheaters, and intercoolers, in addition to improving the full-load economy, has an even greater effect in improving the partial-load economy. In the closed cycle, by reducing the gas pressure as the load is reduced, practically full-load efficiency can be maintained at partial loads.

POSSIBLE GAS-TURBINE APPLICATIONS

The possible applications of the gas turbine are many. Ranging from a simple open cycle for small capacities to

a closed cycle for very large ratings it offers wide possibilities. For example:

Locomotives. The simple open gas cycle requires no water. It has low weight and small space requirements combined with simplicity. With an efficiency of 20 per cent at 1,200 degrees Fahrenheit and the expected low maintenance of turbine drives, it should prove a good power plant for a locomotive. The inability of the gas turbine to operate in reverse makes either electric drive or the development of a satisfactory reversing gear necessary for this application.

Airplanes. For relatively small power outputs, such as required by the airplane industry, the gas turbine operating at high speed and high temperature to obtain maximum rating per unit weight of material has real possibilities.

Ship Drives. The combustion gas cycle offers efficiencies equal to the best modern marine steam power plants, which have over-all efficiencies of approximately 25 per cent. Weight and space requirements of equipment are a real factor in the marine application. The gas cycle eliminates the steam generator and steam condenser. The advantage in weight and space undoubtedly will favor the gas cycle, despite the fact that it includes gas compressor, the regenerator heat exchanger, and the large gas turbine. The requirement of astern operation in marine service handicaps the gas turbine, except as an electric drive.

Power. General application of the combustion-gas cycle in the power-generation field probably will not occur until the problems in connection with the use of coal as a fuel are solved. The successful development of the closed cycle is necessary if units of very large capacity are to be built. The maximum capacity for which units can be built in the open cycle will include the majority of industrial applications. There are many special applications in the power-generation field in which the open gas cycle possibly will find early application. Examples are emergency standby service and low-first-cost units on the ends of transmission lines. In these a simple open gas cycle offers may advantages, such as no water required, low first cost, simplicity, small space requirements, and practically automatic operation with few attendants.

Processing. In the industrial field, where both power and process steam are required, the gas turbine has possibilities. It fits well in those applications where the steam required is relatively small in relation to the power load. This is different from the extraction steam turbine where large quantities of process steam per kilowatt are necessary to attain a comparably efficient cycle. Here again, the use of coal as a fuel is necessary for a wide general application.

MANY PROBLEMS AHEAD

In drawing conclusions, it should be remembered that the cycle has only had practical application in very special cases. The full possibilities of any cycle can only be evaluated from successful proof of its economy, first cost, maintenance cost, and reliability. The addition of elements which improve the fuel economy and arrangements of the cycle for large capacities are obtained at a sacrifice in simplicity and at a price. The development of the best system is expected to be costly in time and money.

Metallurgy plays an important part in the gas cycle as the efficiency increases rapidly with increase in top temperature. To obtain materials suitable for operation at higher temperatures the metallurgists are looking at materials similar to the nonforgeable and nonmachinable tool steels. The method of forming these alloys to shape, such as precision casting to size, may revolutionize accepted methods of manufacture. In order to apply such materials, their additional first cost and manufacturing cost must be justified. Any application of such materials must be preceded by careful tests. For heavy-duty apparatus these tests must extend over long periods before the designer can use them with safety. Careful differentiation between applications as to required length of life of apparatus is necessary. The fact that a piece of equipment is operated at 1,800 degrees Fahrenheit for a life of a few hours does not mean that temperatures of that order can be used for heavy-duty applications.

Present developments of the gas turbine are limited to the use of relatively high-grade fuel oils. This one factor is a serious handicap to the gas cycle. There is considerable evidence that oil is being used at a greater rate than new supplies are being found. So in the postwar period necessity may dictate a prime mover which can use coal as a fuel. The gas cycle is definitely limited in application until such time as the problems in connection with the burning of low-grade oil and coal are solved successfully.

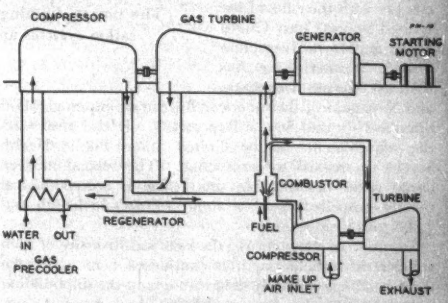

Figure 10. Proposed internally fired closed cycle

Present research efforts are being expended in developments for the war program. In the postwar era industry will have access to the developments in the gas-turbine field and to developments in high-temperature materials. These developments may change considerably present thinking. It is safe to predict that general applications of the gas cycle must wait until the postwar era.

It will be wise to watch the developments of the early installations before attempting to make widespread applications. At present, conclusions as to the ultimate possibilities of the gas cycle are little more than good guesses. The gas-turbine art must advance beyond its present early development stages, before it can be judged with assurance. However, undoubtedly it will find real usefulness in a large number of fields, possibly complementing rather than competing with the steam turbine. Just how and where the gas turbine will be applied, only time will tell.

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Seagoing Electricity

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This article presents a composite picture of the electrical installation on a typical modern peacetime turbine-propelled cargo vessel. The power, lighting, and interior-communication systems are described in detail.

THE COMPLETE electric system of a modern peacetime cargo vessel must comply with the rules of the United States Coast Guard Merchant Marine Inspection Service (formerly the Bureau of Marine Inspection and Navigation), the American Bureau of Shipping, AIEE Standard 45, and Senate Report 184. It also must meet the requirements of the United States Public Health Service in regard to ratproofing. The typical modern cargo vessel described in this article is a hypothetical turbine-propelled vessel of about 450 feet in length and 9,500 tons deadweight.

In order to show clearly the size and diversity of such an electric installation, it is considered here under the three headings generally used throughout the shipbuilding industry: namely, power, lighting, and interior communication. The technical details of equipment are not described, as the principles involved are generally the same as for similar shore equipment. However, all equipment is marine type, suitable for the conditions of roll and pitch, vibration, moisture, and corrosion encountered on shipboard.

POWER

The power system includes all generators, switchboards, motors, controllers, and wiring therefor, except for certain minor motor generators, motors, and switchboards which are integral parts of other systems. Figure 2 shows an elementary one-line diagram of the power system.

There are three 200-kw 120/240-volt three-wire d-c turbine-driven main generators, any two of which will carry the full ship's load. (Diesel-propelled vessels have Diesel-driven generators.) As the rules of the regulatory bodies prescribe a standby generator of a size equal to the largest installed, it is more economical to provide several small generators, rather than one large one, to carry the ship's load, as this reduces the size of the standby generator needed. These generators are flat compound wound and must operate in parallel.

The main switchboard, Figure 3, consists of a generator panel for each generator and panels as necessary for the distribution of power to power-distribution panels, lighting-distribution panels, various separately supplied motors, and so forth. Group control panels are provided for distribution of power to and control of the engine-room auxiliaries. (In some cases the engine-room auxiliaries are fed directly from the main switchboard, and the control panels are located adjacent to the motors.)

A 15-kw 120/240-volt three-wire d-c emergency Diesel-electric generator and switchboard are installed in the superstructure to supply power for emergency lighting, certain of the vital auxiliaries, some interior-communication systems, and interior-communication battery charging, and, through a double-throw switch to provide a feedback to the main switchboard for deadship starting.

Under normal conditions the emergency switchboard is supplied from the main switchboard. Upon failure of or a reduction of 20 per cent in the voltage from the main power plant, the emergency Diesel-electric unit starts automatically and, upon coming up to voltage, is connected automatically to the emergency switchboard by means of an automatic transfer switch which also disconnects the feed from the main switchboard. Upon restoration of voltage on the main switchboard, the transfer switch disconnects the emergency generator and reconnects the feed from the main switchboard.

Duplicate motor alternators are provided for the supply of 115-volt 60-cycle alternating current where required for various interior-communication systems.

Motors are 230 volts direct current, marine type, and, in general, are stabilized shunt wound. They are of open, dripproof, or enclosed waterproof type as required by their location. Motors for engine room and boiler room are designed for operation in an ambient temperature of 50 degrees centigrade and motors elsewhere for operation at 40 degrees centigrade. Pump motors and ventilation motors have 25 per cent speed reduction, and forced-draft-fan motors 60 per cent. Windlass and warping winch motors are compound wound, and cargo-winch motors are stabilized series wound. Steering-gear motors are shunt wound, constant speed. There are about 110 motors installed, varying in size from one-sixth to 65 horsepower.

Controllers for auxiliaries are of the magnetic type for large sizes, and manual across-the-line type for the smaller sizes, four horsepower 230 volts and two horsepower 115 volts and under, where automatic operation is not required. These starters are divided further into two types, low-voltage protection and low-voltage release. Upon failure of voltage, the low-voltage-protection controllers drop out and must be restarted manually, while the low-voltage release type automatically will restart the motor upon restoration of voltage. The low-voltage release type generally is used for vital auxiliaries. The use of the low-voltage-protection type for nonvital auxiliaries decreases the load on the generator when the power supply is restored after failure.

Warping winch and windlass controllers are full-magnetic reversing type. Cargo-winch controllers are full-magnetic reversing dynamic-lowering type. A recent

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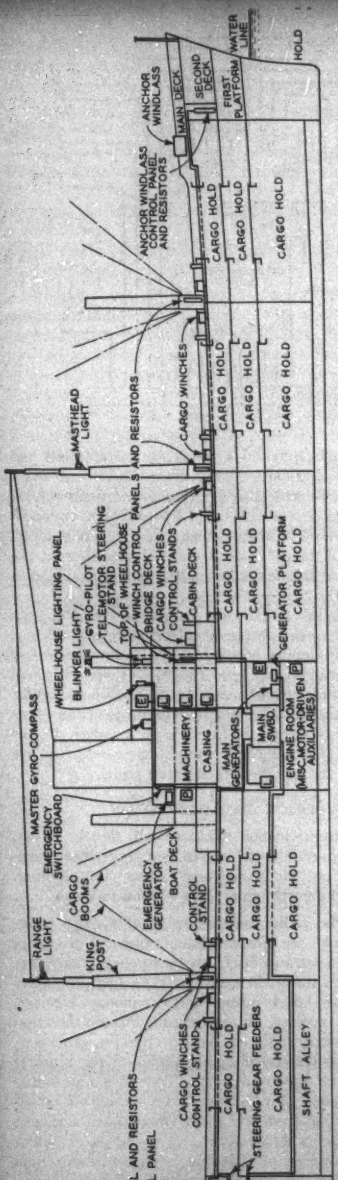

Figure 1. Side elevation showing approximate location of electric equipment on a typical merchant vessel

One-quarter inch equals 12 feet approximately

L—Lighting-distribution panel
E—Emergency lighting-distribution panel (fed from emergency switchboard)
P—Power-distribution panel

Also in wheelhouse:
Engine-order telegraph
Shaft-revolution indicator
Echo-sounding indicator
Whistle control
General-alarm contact maker
Smoke-detecting cabinet
Telephones
Voice tubes
Call-bell push button
Rudder-angle indicator

development is the use of the unit-type cargo winch, which has all the equipment except the master control stand, mounted in one enclosure and on one base or foundation.

The forced-draft fans are interlocked with a solenoid valve in the fuel-oil line to the boilers, so that no oil can be supplied to the boilers unless the forced-draft fans are operating. This is done to prevent boiler explosions.

LIGHTING

General requirements specify that the vessel shall be lighted adequately throughout with standard marine fixtures of a design particularly adapted for the location in which they are placed. Minimum illumination values are in accordance with the contract specifications. (When these values are not given in contract specifications, they should be in accordance with AIEE Standard 45.) Fixtures are divided into two general classes, watertight and nonwatertight. Watertight fixtures are used in locations exposed to considerable moisture, such as engine rooms, deck lockers, galley, refrigerated spaces, and outside spaces. Cargo holds are provided with a special heavily guarded watertight fixture. Living spaces are furnished with nonwatertight fixtures. Since different types of mountings are required, the fixtures also are divided into two further classes, bulkhead fixtures and ceiling fixtures. Mirror lights, with convenience outlet, are installed over mirrors in toilets and staterooms. There are berth lights for each berth, and desk lights for all desks.

Switches are watertight or nonwatertight in conformity with the fixtures as previously described and are single pole. Where spaces have two or more entrances, three-way or four-way switches are used, so that the lights may be controlled from any entrance. Switches for refrigerated spaces are located outside the doors and equipped with pilot lights.

Convenience receptacles, watertight or nonwatertight as required by the location, are provided where needed throughout the vessel.

General lighting-distribution panels are fed from the main switchboard, are 115/230 volts three-wire direct current, and are of the door-in-door type. Switches in these panels are of the circuit-breaker thermal-overload-trip type rated at 30 amperes, 115 volts. One spare switch is installed for each eight switches or fraction thereof.

All lighting circuits beyond the distribution panels are 115 volts, two wire. Ceiling lights and bracket lights are on separate circuits. Bracket fans and convenience receptacles are on separate circuits from the lights.

Floodlights are provided for illumination of the deck and hatches while the crew is working cargo, and boat-launching floodlights for the illumination of lifeboats while these are being loaded and lowered over the side. The boat-launching floodlights are connected to the emergency lighting system and controlled by switches in the wheelhouse.

Loads on lighting branch circuits are limited to 880 watts (1,120 watts for the duration of the emergency). Motors larger than one-quarter horsepower or other devices consuming more than 660 watts (1,320 watts for the duration of the emergency) must not be connected to lighting circuits.

Emergency lighting is installed as required in passageways, engine rooms, and so forth, in order to furnish

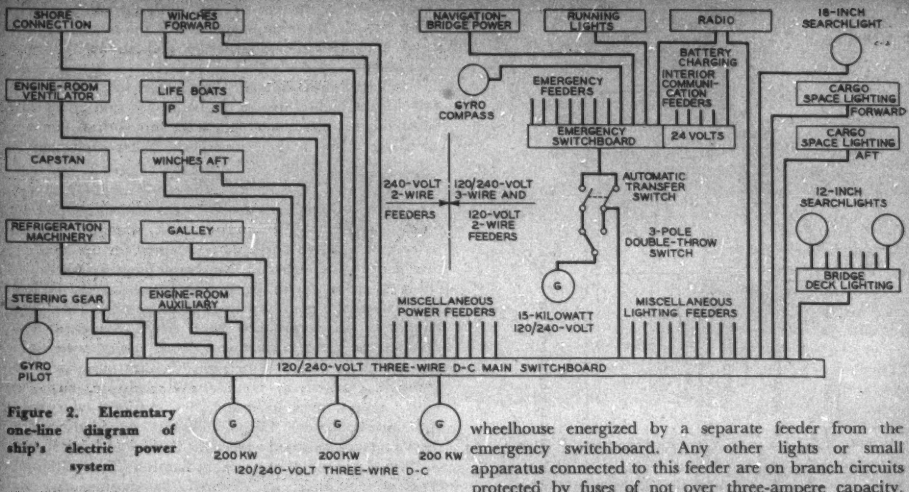

Figure 2. Elementary one-line diagram of ship's electric power system

sufficient illumination for emergency escape, or emergency repairs. Receptacles connected to the emergency system are located in the engine room and engineer's workshop. Emergency lighting circuits are fed from separate distribution panels connected to the emergency switchboard. There are no switches on these circuits except in the distribution panels.

The running lights consist of two side lights, masthead light, range light, stern light, anchor lights, towing lights, and not-under-command lights. Masthead, range, stern, and side lights are of the double-filament type and are connected to the telltale panel. Anchor, towing, and not-under-command lights are single filament and are connected to receptacles on the emergency lighting system. (These lights also may be connected to the telltale panel if desired.)

Running lights are controlled by a telltale panel in the wheelhouse energized by a separate feeder from the emergency switchboard. Any other lights or small apparatus connected to this feeder are on branch circuits protected by fuses of not over three-ampere capacity. The telltale panel indicates, both visually and audibly, the failure of a lamp. When one switches over to the reserve lamp or filament, the audible and visual signals are reset.

All-around blinker lights are located on the king posts and connected to the emergency lighting system. These lights are controlled by telegraph keys in the wheelhouse and on each bridge wing.

A separate feeder from the main switchboard is used for the 18-inch searchlight. This searchlight is of the pilothouse control type and is fitted with a switch in the wheelhouse. The two 12-inch signaling searchlights are supplied from the bridge-deck lighting panel.

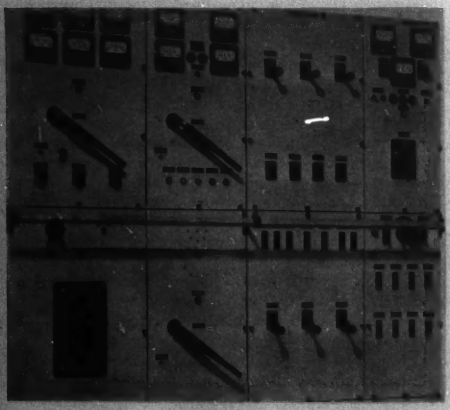

Figure 3. Main switchboard—dead-front type

INTERIOR COMMUNICATION

Interior communication includes all signal, alarm, indicating, and radio systems—in fact, everything electric which is not included under power and lighting. A list and brief description of these systems follows:

Radio. The radio system consists of a main transmitter covering the intermediate-frequency channels, a high-frequency transmitter, an emergency transmitter (combined with the main transmitter), a high-frequency receiver, a low- and intermediate-frequency receiver, an emergency receiver, an auto alarm, a radio direction finder, all necessary batteries, battery chargers, generator, and antennas. This installation must meet the requirements of and be approved by the Federal Communications Commission. Two 230-volt d-c sources of power are provided, one from the main switchboard and one from the emergency switchboard. A recent development is the use of console or unit-type equipment, in which all possible parts are mounted in one housing.

Gyro-Compass System. This system comprises a master gyro compass and repeaters located throughout the vessel as required for navigation. The power supply is from the 230-volt bus on the emergency switchboard.

Gyro-Pilot System. The gyro pilot is of the two-unit type providing an electric telemotor system which parallels

the ship's hydraulic telemotor system and affords automatic steering of the vessel. Power is supplied from the steering-gear feeders and is 230 volts direct current.

Echo-Sounding System. The echo-sounding system is used for determining the depth of water. It consists of a supersonic transmitter and receiver installed in the bottom of the vessel, an indicator which gives the depth of water directly, and a recorder. The indicator is mounted in the wheelhouse and the recorder in the chart-room. Power supply is 115 volts direct current from a power panel to the motor alternator supplied with the equipment.

Whistle Control. The whistle is equipped with both mechanical and electric control. The mechanical control consists of mechanical pulls located in the wheelhouse and on each bridge wing. The electric control consists of contact makers located in the wheelhouse and on each bridge wing, a timing contactor, and a solenoid-operated valve at the whistle. The "at-will" signal, when made from any of the three electric controls, will discontinue the "automatic" signal until the "automatic" signal is restored from the wheelhouse. Automatic signaling is used during fog and, by means of the timing contactor, may be set for five-second blasts at intervals of 1, $1^1/_2$, or 2 minutes. The emergency switchboard supplies 115 volt d-c power.

General Alarm System. The function of this system is to warn the crew in an emergency. It consists of a contact maker located in the wheelhouse, and eight-inch gongs located so as to be audible in all sleeping, working, and recreational spaces. Fused branch boxes, located above the bulkhead deck are furnished for each gong. This system is supplied from duplicate 24-volt interior-communication batteries located in the battery room.

Smoke-Detecting System. This system consists of pipes running to all cargo holds and other spaces to be protected, through which a constant current of air and thus any smoke are drawn. The appearance of smoke in the detecting cabinet can be seen and also will sound an alarm. The power for this system is 115 volts direct current from the emergency switchboard.

Sound-Powered Telephones. Two sound-powered magneto-ringing common-talking telephone systems are provided, a deck system and an engineer's system. The deck system includes telephones in the wheelhouse, captain's quarters, steering-gear room, emergency steering station, bow, and radio room. The engineer's system

Figure 4. 200-watt watertight lighting fixture for engine room

Figure 5. Watertight bulkhead fixture for general use

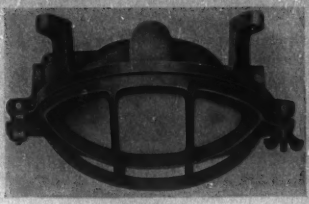

Figure 6. 200-watt watertight lighting fixture for cargo holds

Figure 7. Non-watertight lighting fixture for quarters

affords communication among the wheelhouse, engine room, chief engineer's quarters, emergency generator room, and steering-gear room. All stations on a system are intercommunicating.

Voice Tubes. Voice tubes are installed for communication between the gyro-compass room and the wheelhouse magnetic compass, the wheelhouse and radio room, and the wheelhouse magnetic compass and the standard compass on the housetop.

Call-Bell System. All passenger staterooms, officer's staterooms, wheelhouse, radio room, and similar spaces are equipped with push buttons connected to an annunciator and bell in the pantry or galley. The power for this system is from the duplicate 24-volt interior-communication batteries.

Refrigerated-Spaces Alarm System. All refrigerated spaces having doors which can be so locked from the outside that they cannot be opened from within have push buttons connected to an annunciator and bell in the galley to provide an alarm in the case of personnel being locked in these spaces. The current for this system is obtained from the 24-volt interior-communication batteries.

Engine-Order Telegraph. The engine-order telegraph system consists of transmitters with reply equipment in the wheelhouse, on the wheelhouse top, and on each bridge wing; an indicator with reply equipment located at the engine control station; and one indicator without reply equipment at the boiler control station. This system may be of either the mechanical or the self-synchronous electric type. If self-synchronous, the power is obtained from the common interior-communication motor alternators.

Shaft-Revolution Indicator. The shaft-revolution indicator is of the magneto type, with the magneto connected to the shaft and with indicators in the wheelhouse and at the engine control station. The magneto has a mechanical revolution counter and the indicators have electrical counters. The wheelhouse indicator also has dial illumination with a dimmer rheostat. Current for the dial illumination and the electrical counter is obtained from a 115-volt lighting circuit.

Rudder-Angle Indicator. A self-synchronous rudder-angle indicator is equipped with a transmitter at the rudderhead and an indicator in the wheelhouse. The wheelhouse indicator has dial illumination, with dimmer, connected to a lighting circuit. The a-c supply is from the common interior-communication motor alternators.

Electric Pyrometer. On steam vessels an electric pyrometer is connected to a thermocouple at the gas outlet of each boiler and to a selector switch. On Diesel vessels the thermocouples are installed in the exhaust from each cylinder and the common manifold, for the main engine, and in the common exhaust manifold for the auxiliary engines. Where the auxiliary engines are of sufficient size, thermocouples also are provided for each cylinder. The pyrometers are of the high-resistance direct-reading type with automatic cold-junction compensation.

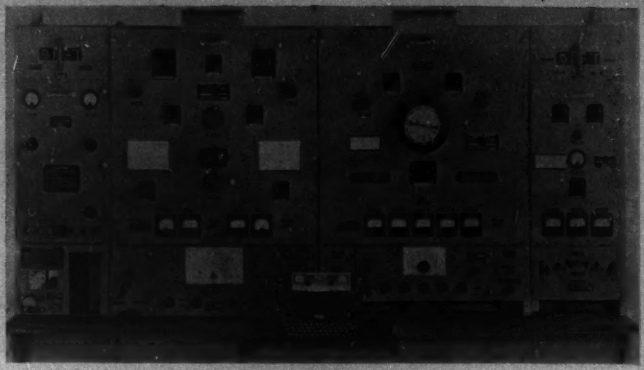

Figure 8. Console-type radio equipment

Lubricating-Oil Alarm. The lubricating-oil alarm consists of a horn actuated from pressure switches located below the lubricating-oil gravity tanks. This system is supervised and is energized from the 115-volt bus in the engine-room emergency lighting panel.

Fuel-Oil-Filling Alarm System. Unless furnished with a common standpipe system, each fuel-oil and settling tank is equipped with an alarm to indicate when the tank is practically full. On a common standpipe system, the alarm is provided only for the settling tanks. Current for this system is obtained from the 115-volt lighting system.

Salinity-Indicator System. This system indicates the amount of solids in the feed water and gives an alarm when the concentration at any cell exceeds the alarm setting. Cells are located as required by the feed-water system. Power is obtained from the motor alternators. (A similar system is used for evaporator plants when installed.)

DEAD-SHIP STARTING

As a matter of interest, the procedure for dead-ship starting is as follows:

1. Start emergency generator, energize emergency lighting in engine room, and otherwise clear the emergency switchboard as far as possible.

2. Clear main switchboard, except for fuel-oil service pump, forced-draft fans, and necessary engine-room lighting. (If boilers do not contain sufficient water, the feed-water pump may be energized.)

3. Close feed-back switch on emergency switchboard.

4. Start forced-draft fans and fuel-oil service pump.

5. When sufficient steam is available, start one main generator and connect to switchboard when voltage is normal; at the same time open the circuit breaker to the emergency switchboard. The emergency generator and the main ship's service generator are not operated in parallel.

6. The loads on the main switchboard then can be energized up to the capacity of one generator. The second generator is started and the remainder of the load connected to the main switchboard.

7. The emergency generator then is stopped, the feed-back switch thrown to the normal position, and the emergency-switchboard circuit breaker on the main switchboard closed.

Figure 9. Gyro-pilot steering stand

CONCLUSION

Because of the present war emergency, none of the special electrical features have been included in the description of this installation. These special features require some modifications and additions to the systems mentioned and also increase the load on the ship's generators. Although the ship described in this article does not include all equipment and systems that may be and are installed on various cargo vessels, it is sufficiently typical to enable a reader unfamiliar with merchant craft to obtain a general idea of the electrical installation on such a vessel.

Electronic Devices Aid Metallurgical Research

E. V. POTTER

Electronic devices found useful in metallurgical research in the fields of ore dressing, hydrometallurgy, pyrometallurgy, and physical metallurgy are reviewed in this article. Use of these instruments for temperature measurement and control, length and displacement measurements, and magnetic testing, and in induction furnaces and chemical and spectrographic analyses is discussed.

ELECTRONIC apparatus and equipment using elec tronic circuits in their operation cycle are so numerous in metallurgical work that any attempt to discuss each application, even briefly, is not possible in any article of reasonable length. Without attempting to cover the field completely, the following list of general applications will give some idea of their extent:

1. High-voltage low-current rectifiers for use with electrostatic separators, X-ray diffraction units, and electrostatic precipitation equipment.

2. Low-voltage high-current rectifiers to replace motor generator sets in electrolytic processes.

3. Electron microscopes.

4. X-ray tubes for both hard and soft radiation for radiography and diffraction work, respectively.

5. Phototubes for applications such as colorimeters for chemical analyses, densitometers for spectrographic and X-ray measurements, color analyses, and smoke detectors.

6. Cathode-ray tubes for use as oscillographs and visual detectors for making numerous measurements.

7. Stroboscopes for observing the behavior of structures and materials under dynamic conditions.

8. Furnace controllers using vacuum tubes and phototubes, and many other applications using combinations of various types of electronic circuits and devices to perform special operations.

This article is concerned primarily with the applications which have been found useful in metallurgical research in the fields of ore dressing, hydrometallurgy, pyrometallurgy, electrometallurgy, and physical metallurgy. The first four fields do not lend themselves to such diverse applications as does the field of physical metallurgy, but such apparatus as electrostatic separators, automatic furnace controllers, induction furnaces, rectifiers, microscopes, and X-ray diffraction units are used widely and involve electronic devices. Also in the associated chemical work, titrimeters, conductivity bridges, colorimeters, pH meters, and polarigraphs employing electron tubes find extensive applications. Many of these pieces of equipment need no discussion, because they have been described many times, and their operation is well known. Therefore, the more special and unusual applications, especially in the field of physical metallurgy will be the only ones discussed in this article.

TEMPERATURE MEASUREMENT AND CONTROL

Probably the most important factor in metallurgical research is the measurement and control of temperature, and the range to be covered is very wide. In work involving temperature differentials, differences in the order of 0.1 to 50 degrees centigrade are encountered, while in other work a range of 0 to 1,200 degrees centigrade is quite common. Direct measurements of these temperatures can be made readily by resistance thermometers or thermocouples, but a form of self-balancing photoelectric potentiometer has been found very convenient for these measurements, because it requires no manipulation and can be used for recording the temperatures on oscillographs, recording milliammeters, or any type of recording mechanism not requiring more than ten milliamperes of current to energize it.

A potentiometer substantially the same as the one now in use was described by R. W. Gilbert[1] in 1936; it is available commercially from several manufacturers. The circuit diagram for this instrument is shown in Figure 1. It consists of two phototubes V_1 and V_2, a high-amplification-factor triode V_3, two voltage regulators V_4 and V_5, a damping circuit R_5 and C_1, a protecting resistor R_1, standard resistor R_s, output current instrument M_1, galvanometer G, lamp L, and prism P. The principal of operation is to vary the current through the standard resistor R_s so that the potential drop across the potential terminals of R_s balances the potential e applied across the input terminals. When this condition is true

$$e = i_s R_s$$

and the output current i_s is proportional to the unknown voltage e applied to the input terminals. Without elaborating on the theory of operation, i_s can be said to vary with the plate current i_p of tube V_3, which is determined by the potential of the grid of V_3 relative to its cathode. Under typical operating conditions, the currents might have values of i_s = 3 milliamperes, i_p = 3 to 13 milliamperes, and i_s = 0 to 10 milliamperes.

The automatic operation is obtained by connecting the galvanometer G in series with the unknown potential e and resistor R_s. The light from lamp L is reflected from the mirror of the galvanometer to the prism P, where it is split into two beams, one going to each of the phototubes V_1 and V_2. Then, if the galvanometer has the proper polarity, any unbalance between the input voltage e and the potential drop across R_s will cause the galvanometer to deflect, changing the relative amounts of light on V_1 and V_2 and thereby changing the grid potential and plate current of V_3, until the voltage $i_s R_s$ is nearly sufficient to balance the potential e. If the galvanometer G had no restoring force, the value $i_s R_s$ would equal exactly e, but, when the suspension exerts some torque, enough current must flow through the galva-

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nometer to maintain the deflection required to shift the light beam enough to maintain the currents i_p and i_s. Thus, we have an instrument which automatically will maintain a current i_s nearly proportional to the unknown potential e, and the value of e can be read directly on an instrument M_1, the calibration factor depending on the value of R_s. Also, any recording device, operating on less than ten milliamperes, can be connected to the output terminals, and a permanent record of the changes in potential e can be made. In addition to its versatility, this potentiometer can be used even when the polarity of the potential e reverses. When e is zero, i_p is equal to three milliamperes, and so reversal of the polarity of e will reduce i_p to a lower value, reversing the direction of i_s and again balancing i_sR_s and e. The sensitivity in this direction is decreased, however, and the range of i_s is limited to a maximum value of three milliamperes as compared to ten milliamperes in the opposite direction.

In actual operation, one of these instruments required a galvanometer deflection of one millimeter at meter distance to shift the current i_s from zero to ten milliamperes. The galvanometer sensitivity was 1.4×10^{-6} volt, showing that between zero and the maximum current of ten milliamperes the potential drop across the galvanometer changed by 1.4×10^{-6} volt. If the mechanical zero of the galvanometer corresponded to $i_s = 0$, this absolute value of 1.4×10^{-6} volt would be the difference between the value of e and the product i_sR_s corresponding to a maximum current of $i_s = 10$ milliamperes. If the mechanical zero corresponds to other values of i_s, then the drop in potential across the galvanometer may be more or less than this value. In any case, the potential drop and error will not exceed 5×10^{-6} volt, which is as close as measurements ordinarily can be made with the usual types of potentiometers. Actually, in any potential range exceeding 0 to 0.5 millivolt full scale, this error is less than one per cent, and thus the instrument M_1 or the recording mechanism will limit the accuracy of the measurement.

Potentiometers of this type can be made to have ranges as low as ten microvolts and as high as ten volts full scale. Thus, with chromel–alumel thermocouples, temperature differences as low as 0.025 degree centigrade can be measured readily, and the range from 0 to 1,200 degrees centigrade is very readily and accurately measured. A typical laboratory-model instrument is seen in the upper left-hand corner of Figure 2.

The accurate control and regulation of furnace temperatures are very important in all metallurgical processes and research, and a wide variety of instruments have been developed to maintain constant temperatures or to vary temperatures automatically according to a predetermined time schedule. These instruments generally make use of the expansion of metals, generation of an electromotive force by a thermocouple, or the change in resistance of an electric conductor to actuate the controlling mechanism. All these actuating methods can be used with electronic devices, but electron tubes are most generally used in conjunction with thermocouples or resistance thermometers. Several of these controllers will be described.

A very common type of controller uses a thermocouple, a millivoltmeter with a metal vane mounted on the pointer, and a vacuum-tube oscillator. The tuning and feed-back coils of the oscillator are arranged so that the vane moves between them, and the change in the oscillator plate current from the oscillating to nonoscillating condition or the change in plate current with change in frequency is used to actuate a relay and regulate the power to the furnace.

A typical circuit diagram is shown in Figure 3. The oscillator circuit is arranged so that the coupling between L_1 and L_2 prevents the circuit from oscillating when the vane is not between the coils. At low temperatures the plate current through M_1 is high and the heat is turned on. As soon as the vane enters the space between coils L_1 and L_2 and the coupling between L_1 and L_2 is decreased sufficiently, the tube will start to oscillate; this causes the plate current through M_1 to decrease suddenly, opening the relay and turning off the power. Another arrangement is to have the tube normally oscillating with a low plate current, so that the oscillations cease when the vane reduces the coupling between L_1 and L_2; the sudden increases in plate current operates a relay which turns off the power. Still another variation on this general type is to let the vane on the millimeter needle change the frequency of the oscillator, the change in plate current associated with the change in frequency being used to activate the power relay.

The potentiometer type of controller is very accurate and has found very wide use. The electromotive force of a thermocouple is balanced against the voltage drop in an adjustable slide-wire resistor, any difference between the two potentials being used to activate the control mechanism. These controllers can be subdivided into two groups, one in which a galvanometer is used to detect the unbalance between the potentials and to activate the controls, and one in which the unbalanced potential itself is used to activate the controls. The first group includes instruments mechanically activated by the galvanometer as well as those in which a light beam reflected from the galvanometer mirror activates the controller. The first type will not be discussed in this article, because no new electrical devices are involved.

A typical diagram of the second type is shown in Figure 4. When no light is shining on the phototube, the grid bias on the vacuum tube is sufficiently negative to prevent any appreciable flow of plate current through the relay. When the galvanometer deflects enough to reflect the light beam onto the phototube, the grid bias becomes more positive, and the plate current in the vacuum tube increases suddenly to 15 milliamperes or more, activating the relay. The light beam is in the form of a rectangle, about 2 millimeters wide and 15 millimeters high, and a

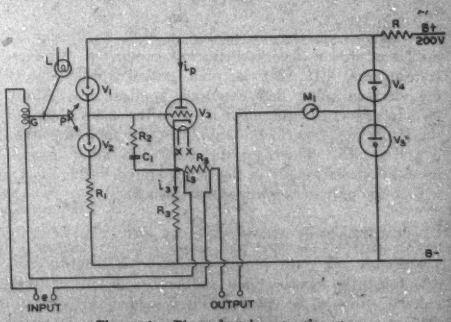


Figure 1. Photoelectric potentiometer

Figure 2. Thermoanalysis apparatus

shield over the phototube provides a sharp edge so that a motion of the galvanometer sufficient to shift the beam less than its width will cause the relay to open or close. This type of controller is sufficiently sensitive to operate in a temperature range of one degree centigrade. One of these instruments is seen on the left-hand side of Figure 2.

It is evident that the self-balancing photoelectric potentiometer previously described could be used as a controller just as well as the photoelectric type shown in Figure 4. However, it is not so sensitive as the other type, because, in order to produce a sufficient change in current to get positive relay action, the input voltage would have to change a proportionate amount. This would correspond to a rather large change in the thermocouple temperature and certainly would not be comparable to the one-degree-centigrade range of the type just discussed.

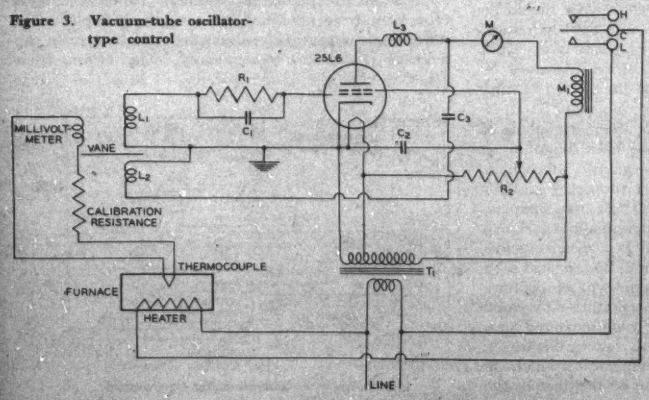
There are two controllers which use the unbalance in voltage between the thermocouple and a potentiometer to actuate the controls without a galvanometer. One of these types is shown in Figure 5. The d-c unbalance potential between the thermocouple and the potentiometer is converted to an a-c voltage by means of a carbon microphone alternately compressed and released at 60 cycles per second. The converted voltage is fed through a step-up transformer to the voltage amplifier and then to the grids of two thyratrons. Depending on the polarity of the d-c unbalance voltage, one thyratron or the other will fire and activate a relay to turn the heating power on or off.

Another type accomplishes the same result by using a 60-cycle operated vibrator to apply the unbalance voltage alternately to one of two windings on a transformer. An a-c voltage is produced in the secondary winding, which after amplification can be used to activate two thyratrons as in the circuit just discussed.

Another type of controller uses the variation in resistance of a resistance thermometer to operate the control circuit. The thermometer is one arm of a Wheatstone bridge, the bridge being in balance at the desired temperature. Any deviation of the temperature from this value will unbalance the bridge, producing a potential across the detector junctions of the bridge. This potential is amplified and used to excite the grids of two thyratrons as in the controllers just described. Unbalance in one direction will cause one thyratron to conduct plate current while unbalance in the other direction will cause the other thyratron to conduct plate current and operate a relay.

Each of the three types of controllers just discussed can be used also for recording temperatures. In the first two the relays are replaced by a motor which rotates the slide on the potentiometer slide wire so as to restore balance. A pen attached to the slide arm then can be used to record the temperature. In the Wheatstone-bridge type the motor would be used to vary a resistor in the bridge circuit and restore balance; a pen attached to the resistor or motor would record the temperature.

Figure 3. Vacuum-tube oscillator-type control



Another arrangement used as a temperature recorder employs a bridge composed of two resistors and one fixed and one variable capacitor. The unbalanced bridge potential is amplified and applied to two thyratrons which drive a motor attached to the shaft of the variable capacitor. The motor varies the capacitance to restore balance in the bridge; a recording pen on the capacitor shaft will record the temperature.

All the instruments described so far have been for use in recording or measuring temperatures or maintaining temperatures at fixed values. With

little change they can be readily adapted for operation on predetermined time–temperature schedules. With the controllers using milliammeters to activate the controller circuits, it is only necessary to couple the arm, carrying the oscillator coils to a shaft, activated by a motor-driven cam. The cam can be cut to produce any desired motion of the arm in the milliammeter, and thus the controller will operate to maintain the furnace temperature at a value determined by the cut of the cam.

In the potentiometer-type controller a similar cam arrangement can be made to rotate the slide on the potentiometer slide wire, varying the voltage to correspond to the desired temperature. With the resistance-type controller, one arm of the bridge circuit can be varied so that balance would occur at the desired temperature. The conversion to operation with variable temperatures is largely mechanical and warrants no further discussion in this paper.

Applications of Temperature Measuring, Controlling, and Recording Devices. Apparatus of the type just described can be used to determine important properties of metals, alloys, and clay minerals. For example, one of the important constants of a metal or alloy is the temperatures at which changes in its crystalline structure occur. Proper heat treatment to obtain the desired properties in a metal or alloy require that these critical points be known accurately, and apparatus for determining these temperatures is very important. This can be done as follows:

A specimen of an unknown steel, for example, is placed inside a hollow metal cylinder made of a material which has no transition points in the temperature range to be studied. Thermocouples then are placed in the cylinder wall and in the specimen and connected differentially, so that any difference between the temperature of the cylinder and the specimen can be measured. As the specimen and containing cylinder are heated, the differential will be small and essentially constant until a transition point is reached, at which point the specimen will either absorb or give off heat increasing or decreasing the temperature differential. Thus, in order to determine the temperature at which this transition occurs, the differential couples and the couple in the cylinder can be connected to self-balancing potentiometers which are connected to a dual recorder, and the temperature corresponding to peaks in the temperature differential curve can be readily found. The temperature of the specimen and holder should be increased at an essentially uniform rate for best results, and this is done by using a controller of any of the types described fitted with a cam mechanism for increasing the temperature of the balance point at the desired heating rate.

A very similar application is the thermal analysis of clay minerals. These analyses have been found to be quite useful for differentiating between clays which have very similar crystalline and optical properties and for analyzing clay mixtures which are not too complex. The apparatus for making these determinations is shown in Figure 2. The clays are placed in a metal crucible in a pot furnace (center of Figure 2) and heated at a uniform rate by means of a photoelectric-type temperature controller (left of Figure 2), the temperature differential between the clay and its container being measured on a photoelectric potentiometer (upper right in Figure 2). Each clay will have transitions at temperatures which are characteristic of that material; it can be identified by the

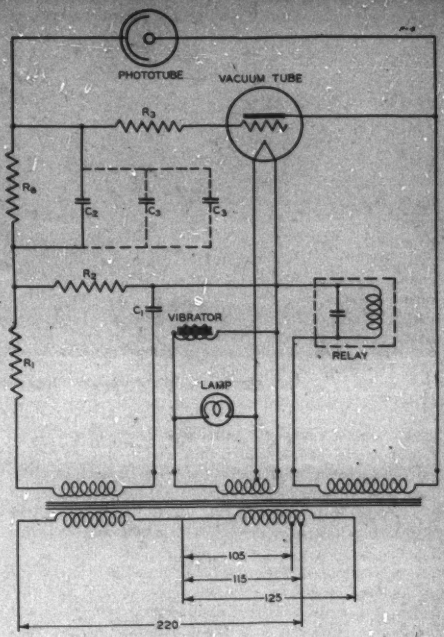


Figure 4. Photoelectric-type control

magnitude of the differential peak and the temperature at which it occurs. In the case of mixtures, the clays composing it can be identified individually from the composite differential curve, and the relative amounts of each type present can be estimated from the area under the differential peaks.

LENGTH AND DISPLACEMENT MEASUREMENTS

The afore-mentioned applications of electronic equipment involved temperature phenomena only, and such applications are limited in number. However, several types of instruments suitable for length or displacement measurements have been developed which increase the field of application tremendously. The measurement

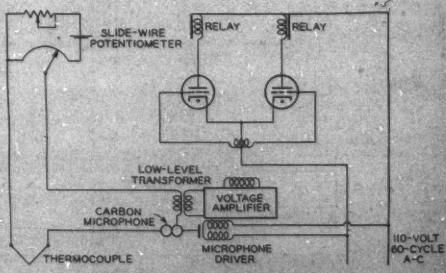


Figure 5. Potentiometer-type control

of absolute length is necessary in many cases, but this can be accomplished quite well by normal methods which need not be discussed. The measurement of changes in length and displacements, both static and dynamic lend themselves readily to electronic methods. These applications will now be discussed.

In dealing with metals, an obvious method for measuring changes in length or displacements is to use the change in electrostatic capacitance between the specimen and a metal plate, caused by the motion of the specimen relative to the plate. This method is fundamentally sound, but a number of difficulties are encountered when the usual methods are used for converting these capacitance changes into electric currents or voltages for recording or measuring. Depending on the type of converter circuit used, difficulties are encountered in obtaining sufficient sensitivity, eliminating interference from local electrostatic fields, and in operation over wide frequency bands.

The Bureau of Mines has been using a circuit which eliminates these difficulties to a great extent. The basic circuit diagram of this converter is shown in Figure 6, and a complete description of it and its operation will be found in a previous publication.[2] It consists of two oscillators, *A* and *B*, very well-isolated and shielded from each other, and a coupling circuit by means of which energy can be transferred from one oscillator to another. The oscillators, which are of the ordinary tickler feed-back type, operate at a frequency of approximately 1,000 kilocycles. The coupling circuit consists of two coils L_1 and L_2 closely coupled to the oscillator tuning coils, a rectifier tube V_1 and a d-c milliammeter M_1. The rectified direct current is indicated on M_1, and the stray capacitance in V_1 and M_1 (C_1) serves as a path for the high-frequency current.

These oscillators operate very much like two a-c generators in parallel. If both are tuned to exactly the same frequency, and the couplings between the oscillators and the coupling circuit are equal, no current will flow in M_1. If the normal frequency of either oscillator is changed slightly by a change in its tuning capacitance, energy will be transferred from one oscillator to the other in order to keep them synchronized, and current will flow through M_1. Thus, over a considerable range of capacitance above and below the value corresponding to identical normal frequencies for the two oscillators, they will continue to oscillate at the same frequency and the current in M_1 will vary approximately in proportion to the deviation of the capacitance from its normal value.

The variation of current with tuning capacitance is shown in Figure 7. The current rises rapidly on either side of a minimum value, and for values of capacitance below or above the limits shown the oscillators will not remain synchronized, and the current will drop suddenly. The minimum current is not zero, as it theoretically could be, because the oscillator circuits and their coupling to the synchronizing circuit are not identical, and some unbalance is always present. It can be seen, however, that the portion of the curve on the high-capacitance side of the minimum current point is essentially a straight line for a wide range in current and capacitance values. By operating in this range, we can obtain a current which is proportional to capacitance. In studying any phenomenon which can be reduced to a capacitance change, it is necessary only to connect this changing capacitance in parallel with one of the oscillator-tuning capacitors, and the current in M_1 will change in proportion to the changes in capacitance.

With this unit, current ranges from 5 to 50 milliamperes can be obtained with a sensitivity of two milliamperes per micromicrofarad with the normal synchronizing circuit and 1.5 milliamperes per micromicrofarad with the 1,000-ohm resistor in the synchronizing circuit. This unit has several important advantages:

1. The shape of the current–capacitance curves and the sensitivity can be controlled readily.
2. The unit is simple to operate.
3. It will respond to changes in capacitance having frequencies from zero to several hundred kilocycles per second.
4. It has low background voltage, the internal noise being approximately 0.003 volt across 1,000 ohms.
5. It is free from interference by local magnetic and electrostatic fields, so long as their frequencies differ appreciably from the resonant frequency of the oscillator circuits.

This instrument in conjunction with the temperature-operated instruments previously discussed has been very useful for making dilatometric, damping-capacity, and modulus measurements.

Applications. Dilatometric measurements are very important in metallurgical research, because they provide a means of studying phase changes in alloy systems as well as of measuring the coefficients of expansion of solid materials. The usual dilatometer consists of a quartz tube closed at its lower end and suspended from a metal base. The specimen to be tested is placed in the bottom of the tube, and a quartz rod is placed so as to rest on the upper end of the specimen. When the outer quartz tube is heated or cooled, the change in length of the specimen causes the inner rod to move relative to the outer tube. An ordinary dial gauge clamped to the outer tube can be used to measure the motion of the inner rod, but for recording the motion it has been found convenient to change this motion into a proportional change

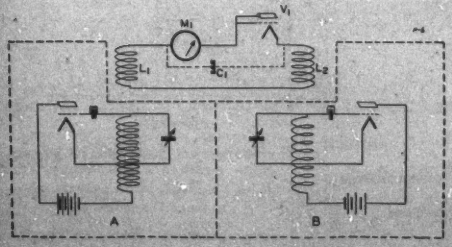


Figure 6. Coupled-oscillator transducer

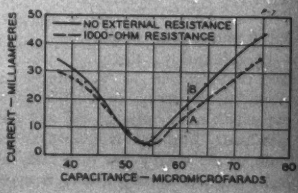


Figure 7. Synchronizing current—capacitance curves

in electric current. This can be done by fastening metal plates to the two quartz tubes and using the change in capacitance between the plates as the inner rod moves to change the current from the converter circuit just described.

A better arrangement, however, is to use two electric strain gauges in a bridge circuit. This arrangement is shown in Figure 8. The strain gauges G_1 and G_2 are cemented on opposite sides of a small strip of plastic material about one-eighth-inch thick, and the strip is fastened to base B at one end and rests on the inner quartz rod Q_2 at the other end. Thus, motion of the rod Q_2 will bend the strip P, compressing one gauge and stretching the other. The two gauges are the resistors R_1 and R_2 in the bridge circuit in Figure 9. Thus, the expansion of the specimen will unbalance the bridge and change the voltage d across the detector terminals of the bridge; and, for small changes in the ratio of R_1 to R_2, the voltage d will be proportional to the change in the values of R_1 and R_2, which are in turn proportional to the displacement of the end of strip P.

Either an alternating or a direct potential can be used across the bridge arms at e. If alternating current is used, the unbalance voltage d can be amplified and measured as alternating current or rectified and measured as direct current. As a direct current, it can be used readily to record the expansion of the specimen. If a direct potential is used, the d-c potential across d can be applied to a self-balancing potentiometer and recorded along with the temperature of the specimen.

By far the most useful application of the electrostatic converter circuit is in the measurement of damping capacity and modulus. Before discussing the technical details, however, it would be better to explain just what is meant by the term "damping capacity."[1]

The phenomena associated with damping capacity are well known in spite of the fact that few are familiar with that term. For example, we say that a piece of lead is dead, meaning that if it is dropped or if a bar of it is struck the only sound it gives off is a dull thud. On the other hand, a piece of steel or brass will emit a sound of very definite pitch if it is dropped or struck. This difference in behavior is caused by the fact that the energy imparted to the lead when it strikes the floor, or is struck, is rapidly dissipated as heat and the vibrations are damped out too quickly for the ear to recognize any definite pitch in the emitted sound. The steel or brass, on the other hand, absorbs the energy at a much lower rate, and the vibrations in the body will continue long enough for the ear to recognize that the sound has a definite frequency. The rate at which vibrational energy in a body is converted into heat is a characteristic of the material, and it is this property we are referring to when we speak of damping capacity.

Quantitatively, damping capacity can be expressed in a number of ways, but the term "specific damping capacity" is the only one we will discuss here. This term is defined as the ratio of the energy lost in a body as heat, when it is subjected to a cycle of stress, to the potential energy stored in the body at maximum stress, and it is usually expressed in per cent. On this basis, lead will have a "specific damping capacity" of 10 to 20 per cent, while steel and brass have values of approximately 0.01 per cent.

Damping-capacity measurements generally are grouped into two classes—high-stress and low-stress. The first group includes all those measurements in which the specimen is subject to stresses over about 100 pounds per square inch, and they are made almost exclusively by subjecting the specimen to torsional stresses. One type of apparatus used for making these determinations is shown in Figure 10. The specimen is made into the form of a rod one-fourth-inch in diameter and five inches long with square ends one inch long and five eighths inch square. One end of the specimen is clamped in a metal frame securely fastened to a large cement block. The frame and the specimen can be seen to the right in Figure 10. A metal bar also visible is clamped to the upper end of the specimen and twisted enough to produce the desired stress in the specimen. The bar is held in this position by electromagnets and released when the test starts. The amplitude of swing of the bar is then recorded, and the decrement of the vibrations can be determined from this record. The specific damping capacity then will be

$$p = 200 \log_e \frac{A_{n+1}}{A_n} \text{ in per cent}$$

where A_n and A_{n+1} are the amplitudes for any two successive cycles. An approximate form is

$$p = (400/n)\frac{A_m - A_{m+n}}{A_m + A_{m+n}}$$

where A_m is the amplitude at the mth cycle and A_{m+n} is the amplitude n cycles later.

The motion of the swinging bar was recorded originally by direct tracing on a revolving drum by a pen attached to the bar, and later photographic recording was used. The electronic converter circuit described before has proved to be more convenient, and an a-c-operated converter is seen in the upper center of Figure 10. The

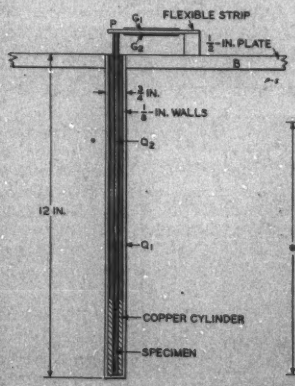


Figure 8

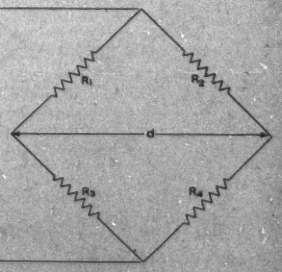


Figure 9

Figure 10. High-stress damping-capacity measuring instrument

motion of the bar is traced on a recording oscillograph as seen in the lower center of Figure 10. The capacitance change required to actuate the converter is obtained from two triangular electrodes mounted on the frame of the apparatus and adjusted so that they are parallel to and close to the moving bar. The motion of the bar will change the capacitance of the capacitors and produce changes in the output current of the converter. This arrangement has been used for several years, and, since the oscillograph will give full-scale deflection for three milliamperes of current, it requires only a capacitance change of 0.75 micromicrofarad to give a curve covering the whole range of the oscillograph. The electrodes need not be large, and the spacing between them and the bar can be considerable.

Low-stress damping measurements are generally those in which the stresses in the specimens are from 0 to 100 pounds per square inch. These measurements are made in two ways: in one case, the specimens are set into vibration and the decrement of the vibrations determined just as in the high-stress tests; in the other case, a method similar to one used for determining the resistance of tuned electric circuits is used. The specimen is mounted on suitable supports and caused to vibrate at a definite frequency by the application of electrostatic or electromagnetic force. The amplitude of the motion will vary with the frequency, being a maximum at the resonant frequency of the specimen.

In this case, a resonance curve is obtained by measuring the amplitude or velocity of the specimen vibrations at frequencies above and below the resonant frequency. Such a curve is shown in Figure 11. The damping capacity is a function of the width Δf of the resonance curve and can be calculated from the equation

$$p = 200\pi\Delta f/f_0$$

where f_0 is the resonant frequency of the specimen.

In one type of apparatus for making such measurements, the specimen is a rod suspended at its center and excited into longitudinal vibration by an electromagnet at one end. The motion of the specimen is determined by measuring the voltage induced in the coil of another magnet at the other end. The motion is very small, however, and the induced voltage must be amplified as much as 50,000 times before it can be determined readily. An amplifier having a gain of 50,000 over a frequency range of 20 to 40,000 cycles per second is used for this purpose; a cathode-ray oscillograph is used for measuring the amplified voltage.

In another arrangement the specimen is clamped to a

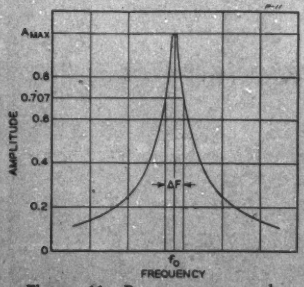


Figure 11. Resonance curve obtained by measuring the amplitude or velocity of the specimen vibrations at frequencies above and below the resonant frequency

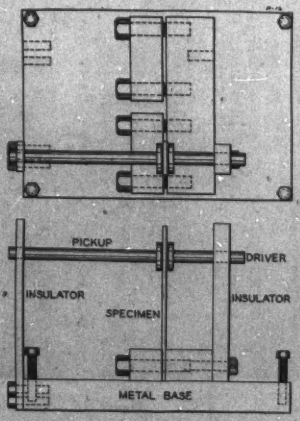


Figure 12 (right). Flexual damping apparatus

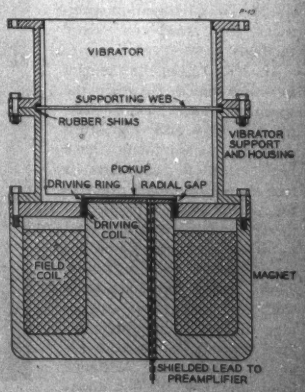


Figure 13. Cross section of sonic generator

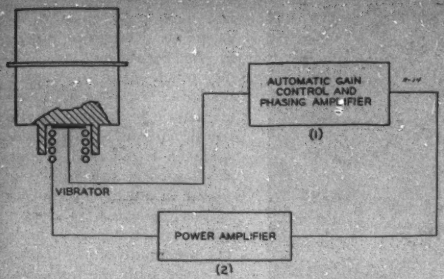


Figure 14. Block diagram of self-controlled sonic vibrator

heavy base at one end and driven at the other end by an electrostatic force. Such an arrangement is shown in Figure 12. A voltage is applied between the specimen and the driver electrode and the change in capacitance between the pickup electrode and the specimen is used to actuate the electrostatic converter circuit previously described. Either resonance curves or decrement measurement can be used with this apparatus.

The characteristics of the converter circuit are seen most clearly in this application. The potential gradient between the specimen and the driver electrode may be as many as 2,000 volts per inch and the pickup electrode is directly opposite, and, even though the specimen is small and offers little shielding effect, the output from the pickup shows no effect from the driving field. Also none of the connections from the pickup electrode and the specimen need be shielded.

In all the low-stress damping measurement, the modulus of elasticity can be determined at the same time that the damping is obtained. From theoretical studies, the resonant frequency of simple forms of specimens is related to the dimensions, density, and modulus of electricity in a simple manner. Thus, by determining the resonant frequency, density, and dimensions, the dynamic modulus can be calculated. These methods can be used on specimens too small for static methods.

In a few cases the changes in capacitance between the specimen and pickup plate in the low- and high-stress damping measurements have been used to modulate a frequency-modulated oscillator, and a simple frequency-modulation receiver was used to demodulate the signal for measurement and recording. This system worked quite well and had the advantage that the measurements and recording could be made at a considerable distance from the rest of the apparatus, but in general it has

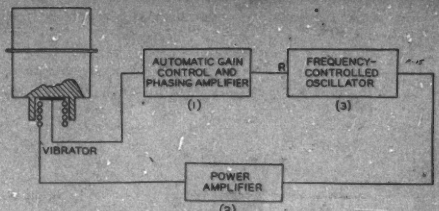


Figure 15. Block diagram of self-controlled sonic vibrator

no advantage over the direct connection to the converter circuit.

APPLICATION OF SONICS TO METALLURGY

The fact that sonic waves of sufficiently high frequency and amplitude would cause the flocculation of solid materials suspended in gases was discovered many years ago; it was thought that this might afford a convenient method for recovering suspended solid and liquid matter from smokes, fumes, and other aerosols. This application was considered first, but the effect of high-frequency waves on the flotation of minerals, on the deposition of metals in electrolytic processes, and on the degassing of metal melts also is being investigated. The primary problem, however, was the development of a suitable source of sonic waves, and a new type of sound generator was developed by the Bureau of Mines especially for this work. Its successful operation is dependent on special electronic circuits; and, since the generator itself already has been described in detail,[4] only a brief description of the essential parts of the generator will be given here.

The sound generator consists essentially of a vibrating member, an electromagnetic driving system, and an electrostatic pickup plate; a cross section of the generator is shown in Figure 13. The vibrating member of this

Figure 16. Sonic flocculating unit

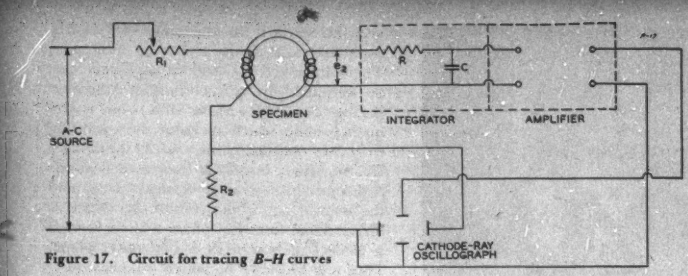


Figure 17. Circuit for tracing *B–H* curves

generator is a solid Duralumin cylinder supported at its midsection by a thin web which is an integral part of the cylinder. The cylinder is free to vibrate longitudinally as a free-free bar; the force producing the vibrations originates in a driving ring on one face of the cylinder. This ring is also an integral part of the cylinder. The driving mechanism consists of a pot magnet with a circular air gap, into which the driving ring fits, and a driving coil wound on the inner face of the air gap. The current to drive the vibrator passes through this coil and, by transformer action, induces a current in the driving ring. The interaction of this induced current with the radial magnetic field in the air gap of the pot magnet produces the force on the driving ring. The electrostatic pickup plate on the center pole of the pot magnet does not contribute directly to the operation of the generator but provides a means for controlling the vibrations. It is insulated from the magnet structure, and a connection is brought out through a hole in the center pole piece. The capacitance between this plate and the vibrator will vary with the motion of the vibrator, and, by suitable means, this capacitance change can be made to produce a voltage the amplitude, frequency, and phase of which are determined by the motion of the vibrator.

The force on the driving ring will be proportional to the product of the current induced in the driving ring and the strength of the field in the air gap of the pot magnet; it will also be in phase with the current in the driving ring which will be essentially 180 degrees out of phase with the current in the driving coil. At its resonant frequency, the cylinder will have its maximum velocity of motion which will be in phase with the driving force. For frequencies above resonance the velocity will lag, and for lower frequencies the velocity will lead. The same relative condition is true of the amplitude except all are displaced in phase by a 90-degree lag. The variation of velocity and amplitude with frequency is the same as the resonance curve shown in Figure 11. In this case, f_0 might be 17 kilocycles and Δf would be approximately one cycle per second. In order to maintain the amplitude of the vibrations near the maximum, it is necessary to maintain the driving frequency within ± 0.2 cycle per second of the true resonant frequency. This is not so simple as it might seem, because the dimensions and elastic constants of the vibrator change with temperature, and the frequency may change as much as 100 cycles per second between its initial value and its value after operating for an hour.

Two driving systems were devised for operating these vibrators; a block diagram of the first is shown in Figure 14. The capacitance change in the pickup plate is converted in amplifier 1 into a potential and is amplified sufficiently to drive amplifier 2, which in turn supplies the power to drive the vibrator. The actual motion of the vibrator will vary with its acoustical load, and thus the voltage generated by the pickup will vary. It is necessary, however, to maintain a substantially constant power input to the vibrator driving coil. Also, the phase of the driving current must be correct relative to the vibrator motion in order to maintain the maximum amplitude of vibration. Thus, the amplifier 1 in Figure 14 was designed with an automatic gain control and a phase-shifting circuit, so that a constant output voltage could be maintained over a wide range of input voltages, and the phase of the output voltage can be changed through practically 360 degrees relative to its input voltage. This oscillator and amplifier circuit is described completely in St. Clair's article[4] and in a Bureau of Mines publication,[5] as well as in an article[6] in the Review of Scientific Instruments.

With this driving arrangement the driving frequency always remains at its optimum value when the phase has been adjusted properly. It has several disadvantages in that the circuit either oscillates or is completely inoperative, in which latter case an external source of voltage must be used to drive it instead of the voltage from its own pickup. Under heavy acoustical loading conditions, the vibrator motion may be so small that the amplifier gain is not sufficient to maintain the vibrations, and the system will cease to function. Also, the vibrations and driving power always are initiated at low amplitude and buildup gradually to a maximum, so that,

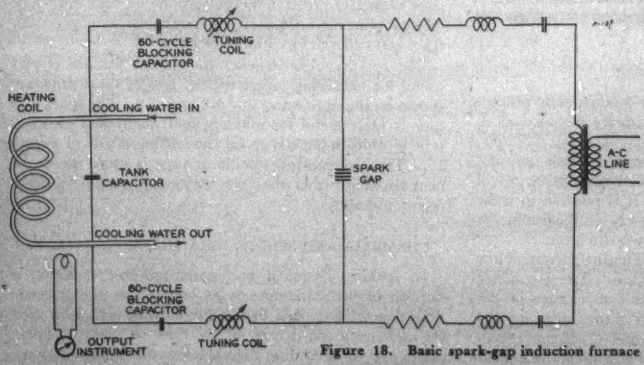


Figure 18. Basic spark-gap induction furnace

Figure 19. Induction furnaces

in borderline cases, where the gain in the system is barely sufficient to maintain oscillations, it may be difficult to get it started.

The other driving system is illustrated in the block diagram in Figure 15. In this case the automatic gain control and phasing amplifier 1 and the power amplifier 2 are the same as before, but an additional oscillator and amplifier circuit 3 have been added. The oscillations are generated in this unit and amplified to drive the vibrator; they are not dependent on the vibrator motion. The variation in phase of the pickup voltage with frequency is used to control the frequency of the oscillator. A complete description of this oscillator and amplifier circuit can be found in other publications.[5,6] When the automatic control is operating, it is possible to change the frequency of the oscillator by 900 cycles per second in 17 kilocycles, while the automatic control will compensate for this change and hold actual frequency within about ± 0.2 cycle per second of the proper resonant value. In addition, this driving system will function under the heaviest acoustic loading of the vibrator, and, even when the vibrator motion is too small for the automatic control to operate, the oscillator still will drive the vibrator if the frequency is adjusted manually from time to time. In addition, this driving system supplies maximum driving power at all times and makes it easier to get the vibrator into motion. A large sonic flocculating unit with a driving circuit capable of developing 2,500 watts of energy is shown in Figure 16.

MAGNETIC TESTING

The best method for determining the magnetic properties of metals is by regular permeameter measurements. In many cases, this equipment may not be available. Also, the accuracy of the permeameter methods may not be required, and the time required for making them will not be warranted. In such cases, it is possible to trace B–H curves directly on a cathode-ray oscillograph. A circuit for accomplishing this is shown in Figure 17.

The specimen is excited by an alternating current of low frequency 20 to 60 cycles per second. The secondary voltage e_2 is proportional to the rate of change of the flux density B, and this is integrated in the integrator circuit R, C. The voltage across capacitor C will thus represent the value of B in both phase and magnitude with very little error if the impedance of R is large compared to C at the operating frequency. The voltage across C will be small and must be amplified by a vacuum-tube amplifier having negligible phase shift over a frequency band which includes the operating frequency and a number of its harmonics. The amplifier output is used to deflect the cathode-ray beam in a vertical plane, and the voltage across the resistor R_2, which is proportional to and in phase with H, is used to deflect the beam in a horizontal plane. Thus a B–H curve is plotted automatically. If the apparatus is designed properly, and the frequency is low enough to eliminate skin effects, the curves thus obtained are sufficiently accurate for many purposes.

In cases where only the coercive force of a material need be determined, a coercimeter is used. This instrument does not involve electronic apparatus directly, but with magnetically weak material, d-c amplifiers[7] or resistance-capacitance-coupled amplifiers with good response at low frequencies have increased greatly the accuracy of the determinations and extended the scope of the instrument's usefulness.

INDUCTION FURNACES

In induction furnaces the heat is generated directly in the object to be heated or melted by means of eddy currents induced in the material itself. The magnetic field required to induce these currents is obtained from three types of electric generators and has frequencies from 15 kilocycles to 5 megacycles. The three sources of electric energy suitable for this work are the rotating electric generator, the resonant spark-gap circuit, and the vacuum-tube oscillator. The rotating electric generator is used for high-power capacitance, up to 250 kw, but its frequency is limited to about 15 kilocycles. For smaller sizes, up to 20 or 30 kw, the spark-gap circuit is used. Such a circuit is shown in Figure 18. The voltage across the secondary of the input transformer breaks down the spark gaps, and oscillations are set up in the circuit, the oscillating current passing through the heating coil and inducing eddy currents in the material to be melted. These circuits operate at frequencies from 80 to 200 kilocycles and use either air gaps or gaps enclosed in inert atmospheres. Electron-tube oscillators are used also, the frequency range being generally from 200 kilocycles to 5 megacycles.

The rotating-electric-generator type of furnace is very useful for preparing larger melts; two of these units are shown on the right-hand side of Figure 19. The spark-gap type is most useful for making small melts and samples, typical units being shown on the left-hand side of Figure 19. The electron-tube-oscillator type is more useful for heat treating rather than the melting of metals to make ingots and alloys.

CHEMICAL AND SPECTROGRAPHIC APPLICATIONS

In making chemical and spectrographic analyses, a number of electronic devices are used. The photoelectric densitometer has been developed, so that it can be used for measuring the density of the lines on spectrographic plates and for recording the values on a continuous chart.

Determinations of the pH of solutions are made almost exclusively with pH meters and electronic titrimeters, and conductivity bridges are used to make accurate titrations, especially in cases where the end points cannot be observed accurately by the eye. Polarigraphs are used for analyzing dilute solutions. In these instruments the variation of current through the solution with applied potential is determined, and sudden changes in current at critical values of potential are used to identify the elements in the solution. The magnitude of the changes can be used to determine the amount of an element present. Some of these instruments record the current–voltage curve automatically.

MISCELLANEOUS APPLICATIONS

A number of other cases where electronic devices are used could be found, a few of these being vacuum gauges, vacuum-tube voltmeters, rectifiers for electrostatic separators, bridge detectors, and sensitive relays. These devices are used extensively, and only a few will be explained.

A-c bridge circuits have been found very useful for making a number of measurements, such as the conductivity of aqueous electrolytes, the conductivity of molten salts, the magnetic properties of metals at high temperatures, and the motional impedance of vibrators. In these cases frequencies from 60 cycles per second to 40 kilocycles per second are employed, and suitable means for determining the balanced condition is very important. Some of the electronic circuits used for this purpose will now be described.

The simplest application is amplification of the unbalanced voltage increasing the sensitivity of measurements in the audible range many times. For inaudible frequencies, heterodyne methods are used to convert the frequency to the audible range before amplification.

Visual detectors, such as the so-called "magic-eye" tube, can be used by rectifying the amplified a-c signal. The response of all these detectors, however, is proportional to the amplitude of the signal and independent of phase, so that independent resistance and reactance balancing cannot be done.

The so-called wattmeter circuit makes it possible to make separate balances for resistance and reactance. One of these circuits using ordinary vacuum tubes and a milliammeter as an indicator is shown in Figure 20. The current through instrument M_1 will be proportional to the product, $e_1 e_2 \cos\theta$, where e_1 and e_2 are the voltages indicated in the figure, and θ is the phase angle between e_1 and e_2. One of these voltages is supplied from the same source supplying the potential for the bridge circuit, and the other is the detector voltage. By shifting the phase of one relative to the other, the reading on instrument M can be made to respond to only one component of the detector voltage, e_2. The balancing is made much simpler in some cases.

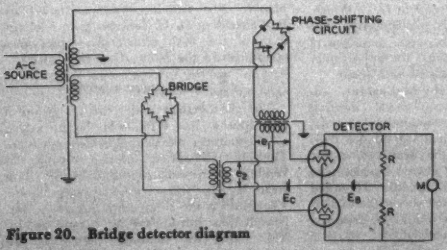


Figure 20. Bridge detector diagram

The great sensitivity of electronic tubes to changes in grid voltage, and the small amount of grid current required to operate them make them very useful as relays. In one case, a thyratron tube is used to determine the point at which the diamond point on a microhardness tester touches the specimen. The circuit operates from any 60-cycle a-c power supply, and the thyratron has a negative grid bias when the metal tube holding the diamond is resting on its support. As soon as the diamond penetrates the proper distance into the specimen, however, the metal tube is lifted from its support and opens a circuit, placing a positive bias on the thyratron. The tube then becomes conducting, and a light in the plate circuit indicates that the diamond impression has been made in the specimen. The extreme sensitivity of this electronic relay makes it possible to reproduce the value of the pressure on the diamond point very closely in making a series of tests, a factor which is extremely important in determining microhardness values.

Another type of electronic relay uses a tube with a diode and a triode element. The diode rectifies the alternating current and supplies direct current for the triode. The grid bias on the triode is changed by external contacts in the grid circuit. This relay is used in a constant-temperature bath, a mercury-column temperature regulator providing the contacts. The change in plate current then will operate a relay and regulate the heating power going into the bath. Temperature control within ± 0.005 degree centigrade can be obtained readily without an inert atmosphere above the mercury column, because practically no current flows through the contacts, and the voltage is small, thus eliminating troubles from oxidation at the mercury surface.

CONCLUSIONS

In conclusion, the afore-mentioned uses of electronic devices in metallurgical research are based chiefly on the work done by the Bureau of Mines, and the general scope by no means is limited to the specific applications mentioned in this article. The cases mentioned will serve to indicate what can be done by electronic means, however, and will show the valuable contribution electronic developments have made toward improving older methods and opening new methods of approach to metallurgical problems.

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INSTITUTE ACTIVITIES

North Eastern District Meeting an Outstanding Success

A very successful wartime technical meeting of the AIEE North Eastern District was held in Boston, Mass., April 19 and 20, 1944, with headquarters in the Hotel Statler. Eight technical sessions and a special session to observe the AIEE 60th anniversary were held during the two days of the meeting, which was preceded by the tri-Sectional technical-paper competition among the Lynn, Pittsfield, and Schenectady Sections on the evening of Tuesday, April 18. Many of the presentations illustrated the electrical engineer's contribution to the war effort in a wide variety of specialized fields. The total attendance was approximately 630, which is appreciably higher than attendance figures for North Eastern District meetings in the past ten years and probably an all-time high for a North Eastern District meeting.

TRI-SECTIONAL COMPETITION

At the technical-paper competition for the younger engineers, first prize was awarded to P. J. Lebenbaum of the Lynn Section for his paper, "Rating Machines—High Altitude," which received 680 points, and second prize to D. K. Hartman of the Pittsfield Section for his paper, "Problems at Boulder Dam," which received 676. All presentations were of such a high order that the decision of the judges resulted in a tie between the Pittsfield and Schenectady Sections, each receiving 1,296 points, and the Lynn Section was not far behind with a total of 1,262 points. The plaque donated by P. L. Alger was presented by vice-president K. B. McEachron to the Schenectady Section to be held for the first six months, and then to be turned over to the Pittsfield Section to be held for the last six.

The judges of the competition were C. A. Corney, R. T. Henry, and H. M. Turner. The audience partly assisted in rating the oral presentations by ballot. President Nevin E. Funk commented briefly on the work of the Institute and the need for putting forth effort to derive the benefits from it. National Secretary H. H. Henline complimented the speakers on their excellent presentations, which were very well illustrated with graphs and charts. R. W. Adams was the presiding officer.

STUDENT TECHNICAL SESSION

A well-attended student session, in which five papers were presented, was held Wednesday morning. The meeting was addressed by President Funk, who complimented the students on their activities and excellent presentations. The first prize was won by H. G. Ryan of Northeastern University, and the second prize went to C. J. Hooker, Jr., of Massachusetts Institute of Technology. G. Minalga presided. The following papers were presented:

Method of Magnetic Recording. **C. J. Hooker, Jr.**, Massachusetts Institute of Technology

Vacuum-Tube Voltmeter With Cathode Followers. **J. B. Angell and A. B. VanRennes**, Massachusetts Institute of Technology

Variable-Frequency 25-Centimeter Oscillator. **H. G. Ryan**, Northeastern University

Electronically Regulated Bias Supply. **R. W. Bordewick and D. E. King**, Northeastern University

Methods of Conducting Student Branch Activities With Army, Navy, and Civilian Student Bodies. **Joseph E. Bambara**, apprentice seaman, United States Naval Reserve, Cornell University

BRANCH COUNSELORS' LUNCHEON MEETING

After the student technical session a luncheon meeting of approximately 20 Branch counselors, students, and Institute officers was held, with R. G. Porter, chairman of the District committee on student activities, presiding. H. W. Bibber, counselor at Union College, explained that, with the transfers from other institutions, social activities were more important in his Branch than heretofore. F. N. Tompkins, counselor at Brown University, commented on his Branch holding joint meetings with other Branch organizations. E. T. B. Gross, counselor at Cornell University, reported on a successful meeting of his Branch, addressed by the director of the college of electrical engineering, which had been held so that the transfers from other Branches could become acquainted. He explained that it was necessary to put the Student Branch at Cornell University on a term basis and that the Branch is fortunate in having in the Ithaca Section some officers who are also in Branch work. He stated that the Section programs were also suitable for students. It was announced that the Schenectady Section had held a dinner for the Union College Branch, which was attended by AIEE Past President D. C. Prince, Everett S. Lee, and A. C. Stevens. The students were seated between members of the Section and thus given the opportunity to become better acquainted with them.

Vice-President K. B. McEachron addressed the Branch counselors' meeting and suggested that the counselors and the Student Branch chairmen should use their ingenuity in building the Branches, as the old methods would not always be successful under present existing conditions. He urged that the good ideas and successful experiments of the Branches should be reported to Institute headquarters.

National Secretary Henline said that 663 Student Branch meetings were reported held or definitely scheduled up to April 10, and he estimated that approximately 700 to 750 meetings would be held during the fiscal year. This compares with an average of 1,257 meetings held during the fiscal years 1938 to 1941, and an average of 944 meetings for the years 1941 to 1943. He advised that one Branch, which had discontinued in the belief that it would not be possible to resume activities until after the war was now reorganized and active again. All Branches were urged to retain their organizations and carry on their activities as well as possible under existing conditions.

The Branch counselors' meeting also was addressed by President Funk and Director R. G. Warner, both of whom felt encouraged by the student activities as demonstrated. The counselors present decided that a meeting of Student Branch counselors should be held within the District next year. H. W. Bibber, E. T. B. Gross, and K. L. Wildes were appointed a committee to handle the balloting for the chairmanship of the District committee on student activities.

AIEE 60TH ANNIVERSARY OBSERVANCE

One of the features of the meeting was a special session held to commemorate the 60th anniversary of the Institute, at which addresses were given by President Funk, Past President Prince, and a representative of the American Airlines, Inc. President Funk in an address entitled "History of the Institute" told where the history can be found, the trends, and the wartime activities. Past President Prince in an address entitled "Future of Electrical Engineering and the Institute" referred to a number of developments in connection with the war effort which might be made available for civilian use in the postwar period, provided there is a sufficient commercial demand. Mr. Prince is chairman of the General Electric Company postwar committee. The representative of the American Airlines, Inc., presented an address on "The Future of Aeronautics," prepared by Edward J. Foley of the American Airlines, Inc., postwar committee, which presented the future possibilities of the commercial airlines after the war, and he presented as problems to be solved, the variable-voltage output of generators and electrical developments required to operate auxiliaries, as well as refinements in lighting for commercial planes. The meeting was conducted by Past President D. C. Jackson, who is chairman of the 60th anniversary observance committee of the North Eastern District.

GET-TOGETHER DINNER

The get-together dinner, with a group of good speakers and William H. Timbie acting as toastmaster, was a memorable occasion. The principal speaker of the evening was William S. Newell, president of the Bath Iron Works, whose subject was "Some Thoughts on the Immediate Future." Mr. Newell was introduced as having world-wide fame for building destroyers. In

Future AIEE Meetings

Summer Technical Meeting
St. Louis, Mo., June 26–30, 1944

Pacific Coast Technical Meeting
Los Angeles, Calif., Aug. 29–Sept. 1, 1944

Annual Meeting

The annual meeting of the American Institute of Electrical Engineers will be held at the Hotel Jefferson, St. Louis, Mo., at 10 a.m. on Monday, June 26, 1944. This will constitute one session of the summer technical meeting.

At this meeting, the annual report of the board of directors and the report of the committee of tellers on the ballots cast for the election of officers will be presented.

Such other business, if any, as properly may come before the annual meeting may be considered.

(*Signed*) H. H. HENLINE
National Secretary

respect to the future and in particular reference to the shipbuilding industry, Mr. Newell explained that, if costs, fixed charges, and inventories were kept down, the industry would be in good shape. He suggested a plan for demobilization, and in conclusion stated that "money, men, and industry must be accorded the same incentives that have been effective in the past."

The meeting was opened by Thomas Cooper, Jr., general chairman, who welcomed the members and guests in attendance and expressed appreciation to the members of his committee for the arrangements made. He explained that the purpose of the meeting was to provide an opportunity for the exchange of ideas and information through the medium of the presentation of technical papers, thus aiding the war effort.

Greetings of the Commonwealth of Massachusetts from Governor Saltonstall were extended by Senator Jarvis Hunt, who expressed appreciation for what electrical engineers are doing for the war effort.

The District prize for best paper was presented to S. Minneci and S. B. Farnham by Vice-President K. B. McEachron. The paper was entitled "A New Control System for Automatic Parallel Operation of Load-Ratio-Control Transformers."

President Funk congratulated the general committee on the success of the meeting, which almost approached the scope of national meetings in character. He expressed the belief that the decision of the board of directors to continue technical meetings during the war is fortunate, because the meetings and many of the papers presented are pointed toward hastening the end of the conflict. The dinner was attended by 567 members and guests.

TECHNICAL SESSION

Seven technical sessions were held during the meeting on subjects as follows: cables, transformers and selected subjects, electronics, power transmission, air transportation, electrical machinery, and industrial power applications. If attendance is indicative of the interest in various subject matter, then electronics and industrial power applications proved to be the most popular, with attendances of 240 and 165, respectively. The papers presented in the electronics session dealt with the development and operation of rectifiers, as well as the control of d-c motors and the application of broad-band carrier systems to telephone cables. The papers in the industrial-power-applications session dealt with voltage regulation, capacitors, power supply for resistance welders, motor control and maintenance, as well as variable-speed drives, and electronic heating, which represented well diversified subject matter in the industrial field.

NATIONAL ....

War and Postwar Topics Scheduled for St. Louis Meeting

The tentative program for the AIEE summer technical meeting to be held in St. Louis, Mo., June 26–30, 1944, promises that it will be the largest summer technical meeting program in the history of the Institute. Arrangements are being made for some 30 technical sessions and conferences, in addition to the annual meeting to be held on Monday, June 26 and the conference of officers, delegates, and members. The occasion also is fitting for a record-breaking program as it will mark the celebration of three important anniversaries in the electrical field—the 60th anniversary of the AIEE, the 100th anniversary of the Morse telegraph, and the 40th anniversary of the International Electrical Congress, which met at St. Louis in 1904. Headquarters for the summer technical meeting will be in the Hotel Jefferson, which has good facilities and some air-conditioned meeting rooms.

TECHNICAL SESSIONS AND CONFERENCES

Several of the technical sessions and conferences will treat subject matter which directly or indirectly aids the war effort. Many new developments to be discussed also will be of great value in the postwar period. Among the sessions and conferences aiding the war effort are: four air-transportation sessions, electric welding, induction heating, and quality control by statistical methods in manufacturing. This latter conference, as well as a conference on electric heating of houses, is especially pertinent to the postwar period.

Several of the sessions which indirectly aid the war effort are of particular interest to the central-stations industry. These are: power generation, power transmission, cables, switchgear, relays, electronic-frequency converters, and power-system applications of carrier current.

Still other sessions and conferences will deal with the following subjects: land transportation, basic sciences, communication, education, electrical machinery, industrial power applications, electronics, X-ray tubes, instruments and measurements, and electrochemistry and electrometallurgy.

REGISTRATION AND HOTELS

Members desiring to attend who receive an advance registration card should fill in and return the card promptly. Hotel reservations should be made by writing directly to the hotel preferred.

COMMITTEES

Those making the arrangements for the meeting are B. D. Hull, *chairman;* I. T. Monseth, *vice-chairman;* L. L. Crump, *secretary-treasurer;* F. A. Cooper, Jr., *chairman,* St. Louis Section. Subcommittee chairmen: C. B. Fall, *finance;* C. H. Kraft, *meetings and papers;* B. T. McCormick, *registration and information;* R. G. Meverand, *hotels;* E. S. Rehagen, *hospitality,* Guy W. Thaxton, *transportation and trips;* L. F. Woolston, *publicity.*

Special Committee to Study Employment Conditions Named

The special committee authorized by the board of directors January 27, 1944 to study employment conditions (*EE, March '43, page 107*) has been designated the committee on collective bargaining and related matters. All but one of the members have been appointed.

The committee members are: I. M. Stein (F '39) director of research, Leeds and Northrup Company, Philadelphia, Pa., *chairman;* O. W. Eshbach (F '37), dean, Northwestern Technological Institute, Evanston, Ill.; W. R. Hough (M '41), engineer in charge of a-c motor design, Reliance Electric and Engineering Company, Cleveland, Ohio; A. C. Streamer (M '41) vice-president, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.; Bartow Van Ness, Jr. (M '35) chief engineer, Safe Harbor Water Power Corporation, Baltimore, Md.; E. P. Yerkes (F '40) engineer of equipment and buildings, Eastern area, Bell Telephone Company of Pennsylvania, Philadelphia. Mr. Stein and Mr. Yerkes also are AIEE representatives on the joint committee with the American Society of Mechanical Engineers on the same subject.

Postwar Electric-Power Development Debated by AIEE New York Section

How co-operative effort between Federal and State regulatory bodies and the power companies can contribute to full development of electric power in the postwar period was aired at a meeting of the power and industrial group of the AIEE New York Section, April 11, 1944. Four scheduled addresses by spokesmen of both the commissions and the power companies covered the various aspects of the subject. The meeting attracted top executives from many of the largest power systems in the United States, especially those having offices in New York. Group Chairman Robert T. Oldfield, senior electrical engineer, New York State Public Service Commission, presided.

Chairman Leland Olds of the Federal Power Commission, Washington, D. C., offered specific suggestions as to how the electric-power industry can meet the challenge of the postwar period. The industry must recognize, he said, that "private enterprise is a trusteeship and must act accordingly. Self-regulation motivated by this moral concept will render government regulation less and less necessary. Toward this objective the power industry has a great opportunity to show the way, and I can assure the men of the industry that we of the regulatory bodies will co-operate."

Expressing disagreement with the policy of the Federal Power Commission, insofar as it seeks to regulate the business of electric utilities doing a wholly intrastate business, Judge Gay H. Brown, former counsel to the New York State Public Service Commission, vigorously defended States' rights in the regulation of such utilities. He cited instances wherein the Federal Power Commission allegedly had gained or sought to gain regulatory control over power companies doing a wholly intrastate business. He urged Congressional enactment clearly defining the authority of the Federal Power Commission as an effective remedy to resist encroachments on state jurisdiction.

The power companies point of view was presented by AIEE Past President John C. Parker, vice-president, Consolidated Edison Company of New York, Inc., who declared that the central-station art must develop responsively to the desires of a free people "so the producers of that service must, to the maximum degree compatible with the general social interest, be free of academic predeterminations and actively responsive to the compulsions of contemporaneous development." He said that wise and tolerant men within the electric-power industry "will cheerfully accept all restraints under law which keep them from wrongdoing and from imposing restraints either by omission or by commission on the communities which they serve."

Stressing the importance of cheap electric power in any community or state that wishes to maintain its industrial importance or to build up its industrial economy, Milo R. Maltbie, Chairman of the New York State Public Service Commission, discussed the place of the power companies in New York State during the postwar period. (As Doctor Maltbie, although present at the meeting, was recovering from a recent illness, his address was read by Maurice C. Burritt, a member of the New York Commission.) Doctor Maltbie pointed out that the principal factors that will enable the power industry to contribute to the continued industrial, commercial, and agricultural progress of the Empire State are: cheap money, adequate reserves, and a reasonable surplus. Companies having a financial structure based upon sound conservative accounting and adequate reserve not only will weather the storm of postwar reconstruction, but also will be able to perform the postwar functions with ease, he declared.

Abstracts of the four addresses follow.

RECAPTURE COMPETITIVE VIEWPOINT SAYS CHAIRMAN OLDS

Predicting that the postwar period will provide industry with a far more difficult test of its devotion to the country's service than the war period with its unlimited consumption, unaffected by costs or prices, Mr. Olds recommended that industry adopt the positive attitude of asking, "How can we sell as much power as during peak war production, and more?" rather than asking, "Will there be a market?"

With the expansion of service set as the postwar frontier Mr. Olds went on to define the postwar power objective in terms of the country's electric-energy requirements. On the basis of supplying energy for full industrial employment, plus the expansion of other classes of energy consumption to provide a steadily rising standard of comfort for the nation, and giving due consideration to reduction in demand and possible new consumer outlets, Mr. Olds placed the objective of the power industry for the end of the first postwar year at an annual rate of between 200,000,000,000 and 220,000,000,000 kilowatt-hours. This amount would be in addition to any power generated in industrial plants and may be compared with about 235,000,000,000 kilowatt-hours which the industry estimates will be generated for public use in 1944. For the end of the fifth postwar year he raised the objective to 270,000,000,000 kilowatt-hours. In specifying these figures, Mr. Olds stressed the fact that he was setting objectives and not forecasting demands.

He praised current ideas of postwar objectives stated in terms of greatly expanded consumption of electricity and adjustment of rates to make it possible. Declaring that the possibilities of expansion become apparent only from a competitive as opposed to a monopolistic viewpoint, Mr. Olds reviewed the tools at hand for restoring competition as a practical force in our economy. He characterized the Federal Power Commission's annual publication of typical electric bills throughout the country as the simplest competitive yardstick for stimulating investigation of costs by publicizing the prices a producer would have to meet to supply a consumer anywhere in the United States. He demonstrated by specific example how an executive of a company could be led, by comparison of his company's rates with those of another with the same cost problems, to a re-examination of costs ordinarily accepted under monopolistic operation. Mr. Olds added that this detrimental acceptance of costs indicates "a point at which monopoly in the power business, even with the help of able regulators, has failed to provide the possibility of full use of resources that would have been offered by free competition."

"I have never heard of a power system assigning a group of engineers to the task of determining the lowest possible price at which electricity could be sold," he said. He declared that engineers more often are given the task of justifying existing rates based on unchallenged costs.

Two other yardsticks for competitive unit-cost tests recommended by Mr. Olds were the Federal Power Commission's annual, "Statistics of Electric Utilities in the United States," and the Commission's, "Directory of Electric Generating Plants." Through these two publications the executive can compare his costs, function by function, with those of his potential competitors.

The striking differentials found in power-company statistics should be "flags, calling attention to matters that should be subjected to managerial analysis," he averred. The relatively high rate of return and the relative abundance of high executive salaries in the industry should be justified by demonstrated efficiency on the part of management, he said. The criterion in the electric field, he asserted, should be the achievement of unusually low costs and rates.

Calling write-ups and the amortization of other excesses over original costs such as the earlier capitalization of intangibles major handicaps to any utility company striving for a postwar outlook of the greatest possible expansion, Mr. Olds urged the adoption of uniform systems of accounting. Uniformity of accounting would not destroy private enterprise, as has been charged, said Mr. Olds, but rather would establish electric-utility accounting on a sound investment basis. Mr. Olds illustrated this contention with the example of a utility company which had reduced its operating expenses $485,000 in two years.

Stating that the obstacles to the full use of power which would vanish in a truly competitive economy must be removed, Mr. Olds upheld the work of the regulatory commissions. He described them as working "to establish an increasing approximation to the capital structure which could be maintained, with maximum security to investors, in a competitive economy. He designated the opposition of certain holding company groups as "reactionary, not conservative. If it were to succeed it would defeat its own ends."

In summation of a program with which the power industry can meet the challenge of the postwar period, Mr. Olds presented the following outline:

1. The industry should accept the obligation which would be enforced by real competition. Each company should set itself difficult sales objectives and should establish rates which would attain those objectives in the face of the most effective competition.

2. To this end the industry should extend cost controls along the lines just discussed. No longer should the costs of a given company be considered sacrosanct.

3. The industry should recognize that, if it reaches a point where it can no longer invest its depreciation reserves in the business, private enterprise will have reached a critical period, for it will be an admission that private capital in this field is no longer enterprising.

4. The industry should form concrete plans for transferring the economies of wartime power pooling to the postwar era. Integrated methods of operation, which would not render the corporate structure unwieldy or so extensive that the industry could not identify itself with the local interests served, should be considered.

5. The industry should assist in broadening the country's economic base through reversing the trend toward industrial centralization and furthering the development throughout the land of a balanced rural-urban economy.

6. The industry should co-operate in the new unitary approach to conservation and utilization of the country's natural resources. This requires establishment of a constructive relationship to the Government's program of water-power development.

RETAIN STATES' RIGHTS URGES JUDGE BROWN

Declaring that the states can adequately regulate the intrastate electric utilities, Judge Gay H. Brown at the outset of his address expressed complete disagreement with the policy of the Federal Power Commission insofar as it seeks to regulate the business of electric utilities doing a wholly intrastate business. Now associated with the law firm of Brown, Ryan, and Kenny, New York, N. Y., Judge Brown was formerly counsel to the New York State Public

Service Commission, and justice of the New York State Supreme Court.

Judge Brown pointed out that Congress passed legislation in 1935 establishing the jurisdiction of the Federal Power Commission, this legislation providing that "Federal regulation shall extend only to those matters not subject to regulation by the states." By means of specific examples, he then showed how the Federal Power Commission had established jurisdiction over power companies doing an entirely intrastate business but having interconnections with systems doing an interstate business. "The Commission claims," he said, "that, where a utility doing wholly intrastate business owns facilities over which some energy is transmitted that finds its way into another State, or if it owns facilities over which any energy received from another state is transmitted, it is a utility under the jurisdiction of the Federal Power Commission." This jurisdiction includes regulation of accounts and records; determination of legitimate cost and depreciation; control of acquisition of stock, sale, or lease of property, and merger or consolidation. He also pointed out that the Commission has extended its jurisdiction over the rivers of the United States to include any stream that could be made navigable by a vessel drawing only two feet of water, even at great expense; this would give the Commission control over practically all the hydroelectric developments in the country.

Characterizing the cases he cited as examples of invasion of States' rights, Judge Brown declared that the only effective remedy to resist such encroachments is by Congressional enactments that will clearly define the authority of the Federal Power Commission.

PARKER PROPOSES FREE ENTERPRISE REGULATED BY NATURAL LAW

At the outset Doctor Parker defined his approach to the postwar course of power production and distribution as a highly tentative one but one that embraced the principles of free enterprise regulated by natural law. He warned that a cart-before-the-horse economy would result unless first things were given first importance in any postwar consideration, or if the cause and effect relationship was misunderstood.

It is the province of engineers, Doctor Parker stated, not to write prescriptions for the future nor to assign the "summum bonum" to a society whose good is fundamentally subjective to its own aspirations and desires, but to appraise realistically some of the facts of life in that society. A first consideration of such an appraisal is a clear concept of the place which our particular art takes in the general social and economic scheme of that society.

It is not deprecatory of the economic and social significance of power development, he continued to realize that it is by no means a primary factor in human advancement, nor even an end in itself; and that, though highly important, it is not in any sense an absolute essential. Electric power, enormously convenient as it is, is still a long way from being indispensable in the sense that the biologic or even the spiritual necessities of life are essential.

Because power systems have been so invaluable an aid to the development of industry and living, it is an easy matter for us to succumb to the fallible belief that the more we have of that particular service the better off we shall be, Doctor Parker explained. Increasing by little or by much the physical capacity of our power systems will not add one iota to the standard of American living nor of American production on which that living must depend. The ability to use must be present first, and only then does our ability to supply gain significance.

Unless the industry of the country finds itself in a social and economic climate conducive to vigorous growth, there will be no increasing use for industrial electric power, whether it be generated centrally or locally, whether it be produced cheaply, expensively, or by subsidy through the taxation of the individual. It is of no consequence how much electricity is available to the homes and farms, or whether the present service charges are decreased or not; there will be no increasing use for electricity unless research and development and commercial distribution of the devices of utilization make that use possible. Even so, there will not be any increasing use unless the people have the means of acquiring these devices and the homes and farms on which to use them.

What is important is that a vigorous and free economy in all fields shall be fostered, whereby the last trivial desire of the citizen may be satisfied if he is willing to work for it, whereby he will be free to accept or to reject what is offered. In our own particular field of power engineering, Doctor Parker stressed, it would mean that such an economy would allow the central power supply to function empirically and not by a predetermined course, anticipating postwar needs as successfully as it has done in the years of preparation for and engagement in combat.

CHAIRMAN MALTBIE STRESSES IMPORTANCE OF CHEAP ELECTRIC POWER TO INDUSTRY

"Of all the various classes of public utilities," stated Doctor Maltbie in his address, "probably none will be subject to more change and readjustments to meet new conditions than transportation and power. Each will have its own peculiar problems but the two will overlap in at least one direction." He then discussed the feasibility of electrifying the main line of the New York Central Railroad in New York State, but pointed out that the role played by electric power in improved transportation facilities is not so important as in industry. "Electric power is an important factor in the cost of manufacturing thousands of articles," he said, "and in many instances it is such an important part of the total cost that the location of industries is in large part and often in major part determined by the price at which electricity can be obtained. Combining all considerations . . . it is clear that in any community or state that wishes to maintain its industrial importance or to build up its industrial economy, the importance of cheap electric power cannot be overestimated."

Paying tribute to the performance of the power companies in New York State during the war, Doctor Maltbie said that: "Notwithstanding certain prognostications to the contrary, there has not been, so far as the Public Service Commission has been able to ascertain, any place in the State of New York where any industry or any industrial development has not been able, even during the last five years of unparalleled expansion, to obtain all the electric power which it desired at the rates then being charged." He hastened to add that every demand has not always been met instantaneously but declared that such instances were generally but minor blemishes on the whole power situation.

"In the discussion of postwar conditions and the part which the power industry will play therein," Doctor Maltbie continued, "one should assume that either through private companies or through the development of governmental facilities, all power demands in the State of New York will be met without any appreciable delay. But when this has been said, we have only started upon the solution of the problem. The fundamental question is not whether at some price electric power will be available to all who are willing to pay that price, but whether electric power will be supplied at the lowest possible cost . . .

"We come then to the question: 'What needs to be done in order that the power industry shall be prepared to make its contribution to the continued industrial, commercial, and agricultural progress of the Empire State?'

"The first factor to be mentioned, possibly not the most important but certainly near the top, is cheap money. Available funds flow freely to all parts of the United States where attractive investments are offered; but everyone knows that speculative or uncertain enterprises cannot obtain capital at as low cost as those in the investment class where risk and uncertainty have been reduced to a minimum. . . .

"Another factor is the extent to which reserves which have been built up meet depreciation and possibly contingencies, such as deferred maintenance or deferred reconstruction which exist in the case of many transportation facilities. Another is the extent to which a reasonable surplus has been provided to cushion any sudden and unusual contingency which could not have been foreseen. . . .

"That company," Doctor Maltbie concluded, "which today has a financial structure based upon sound conservative accounting and adequate reserves is the one which not only will weather the storms of postwar reconstruction, but also will be able to perform its function in the postwar world with ease—safety to its investors and adequate service at reasonable rates to the public."

He closed with a tribute to the utilities that "may not have made the headlines but which were conservatively financed, well engineered, and efficiently operated. Most of them are small, but they are a credit to their communities; their backers can face any investor to whom they recommend the purchase of securities; they will play a prominent and constructive part in our postwar world."

Logan Addresses AIEE Sections on Illumination Service Tour

H. L. Logan (F '43) managing engineer, Holophane Company, Inc., New York, N. Y., addressed several of the AIEE Sections during

his two-month lecture tour of western and southern United States and Mexico in the interests of illumination service. Mr. Logan, who is chairman of the illumination group of the New York Section of AIEE, and the New York section of the Illuminating Engineering Society, spoke on "Light and Safety."

Included in his schedule were lectures before AIEE Sections in Oklahoma City and Tulsa, Okla.; San Francisco, Calif.; and Wichita, Kans.; and before joint AIEE–IES sessions in St. Louis, Mo., and Houston, Tex. Besides engineers, his audience was comprised of other local groups interested in eyesight conservation and safety illumination. Early in June he will speak before the AIEE Mexico Section in Mexico City.

Active Aeronautics Group Interests Dayton Section

A successful series of meeting programs arranged by its new technical discussion group on electrical engineering in aeronautics will be terminated in May by the Dayton Section with a debate between the proponents of alternating and of direct current for the operation of aircraft equipment. The discussion group was suited particularly to the Dayton area because of the proximity of the headquarters of the Army Air Forces Matériel Command at Wright Field, and the Air Service Command at Patterson Field. Moreover many Dayton industries are occupied in manufacturing aircraft equipment.

At the first trial meeting held in February, at which A. W. Braden, major in the electrical laboratory of the AAF Matériel Command presided, there was an attendance of 130 from a membership of about 160. Three 20-minute talks followed by 20 minutes of discussion were scheduled. However audience participation in the discussion was so lengthy that later meetings were limited to two prepared addresses. Topics for the March, April, and May meetings were selected from the preferences expressed by those attending the February meeting.

"D-C Electric-Power Systems in Aircraft" was discussed by R. H. Kaufmann (M '41) of the industrial engineering department, General Electric Company, Schenectady, N. Y., at the February meeting. He presented the problems of paralleling d-c generators in aircraft and methods of making the d-c system "live in harmony." The causes of brush wear at high altitudes and the difficulty of simulating these conditions for test purposes were explained by H. J. Finison (A '43) of the electrical laboratory of the AAF Matériel Command in his speech, "High-Altitude Brush Wear on Rotating Machines." A talk on "Aircraft Lighting" delivered by A. D. Dircksen (A '43) of the AAF electrical laboratory completed the first program. Major Dircksen described the development of ultraviolet aircraft lighting and displayed samples of units and auxiliaries employed since the inception of this method of lighting. He also demonstrated actual units in use.

The March program comprised a discussion by Major Braden of the place of a-c power in the future airplane and the experimental work which has led to its present use in aircraft entitled, "A-C Electric-Power Systems" and a speech, "D-C Power Equipment for Aircraft Radio," by I. H. Gerks, lieutenant colonel of the Signal Corps' aircraft radio laboratory. Colonel Gerks supplemented his presentation with exhibits of d-c aircraft electric-power systems and radio equipment.

Topics for the April meeting were: "D-C Control Systems for Aircraft," and "Effects of Gunfire on Military Aircraft Electric Systems." R. V. White (A '40) field engineer, General Electric Company, Dayton, is secretary of the technical discussion group. T. B. Holliday (M '43) lieutenant colonel, chief of the electrical laboratory, Wright Field, and chairman of the AIEE air transportation committee was one of its originators.

Latest Refinements of Plane Design Described

The electric system of present day bombers has grown into a major part of the design upon which the airplane is dependent for operation and the old system of installing a standard generator and hoping for the best has been discarded for certain methods of evaluation, H. M. Winters (A '40) of The Glenn L. Martin Company's engineering department told members of the Maryland Section at a recent meeting in Baltimore. Mr. Winters presented the paper, "Method of Determining Aircraft Electric Load," in the Section's prize paper contest.

In designing an airplane, Mr. Winters pointed out, it is now necessary to make a load-analysis chart listing each item of electric equipment, the quantity of each item, the operating time, and the number of operations for an average one-hour period. The various conditions under which the items operate including stand-by, starting, take-off, landing, cruising, and taxiing, must be studied. From the detailed and comprehensive data obtained, the demands on the electric system under every possible condition can be deduced to determine the size of the generator needed.

Beaumont Subsection of Houston Section Flourishes

An increase in Institute membership in the area and excellent membership and visitor attendance at its regular monthly meetings are reported by the Beaumont (Tex.) subsection formed in November 1943 under the sponsorship of the officers of the Houston Section. It recently has been proposed that the thriving subsection be the nucleus of a new AIEE Section.

The Beaumont subsection in the extreme eastern part of the Houston Section, where shipbuilding, oil refining, and manufacture of synthetic rubber are the major industries, includes the cities of Port Arthur, Orange, and Beaumont. Since this area lies 90 to 100 miles from Houston, with the imposition of gasoline and tire rationing, travel to Section meetings became difficult. With 23 Institute members thus affected, the Houston Section first experimented with a plan of extended meetings whereby Section meeting programs were repeated the following evening in Beaumont. However, in response to suggestions made at the 1943 AIEE summer meeting in Cleveland, Ohio, the subsection was organized in November 1943.

A motion adopted by the Houston Section defined the purpose of the new subsection: "to permit members belonging to it to attend regular meetings which they would not otherwise be able to do with the meeting place at Houston." The Section agreed to furnish stationery and supplies, to defray other expenses, and, whenever possible, to send its speakers to Beaumont. Local publicity was left to the subsection officers, but all other official Institute matters, publications, and balloting continued under the jurisdiction of the Section. Reports of subsection activities are transmitted to the Section secretary, and the Houston officers endeavor to attend the Beaumont meetings. L. H. Matthes (A '31) resident agent, General Electric Company, Beaumont, was elected subsection chairman and G. W. Morgan (A '37) design electrical engineer, Gulf States Utilities Company, Beaumont, was elected secretary.

Growth of AIEE subsections was encouraged by distribution of a pamphlet from the Sections committee to all Sections during the 1942–43 season. The Sections committee now is studying 15 locations in various Sections where there is a possibility of the successful operation of subsections. At present there are six subsections in operation and two subsections have developed into full Sections.

PERSONAL ••••

C. S. Beattie (M '40) formerly manager of engineering, Delta-Star Electric Company, Chicago, Ill., has been appointed vice-president in charge of production and engineering. A 1923 graduate of Rutgers College, Mr. Beattie gained experience as design engineer with the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., the Public Service Production Company, Newark, N. J., and the United Engineers and Constructors, Inc., Newark. As designing engineer he joined the Delta-Star company in 1930. In 1936 he was made assistant sales manager and in 1941 became manager of engineering. **S. C. Killian** (A '42) formerly development and research engineer is now chief engineer of the Delta-Star company. Before entering the University of Michigan in 1930, Mr. Killian worked for the Delta-Star company as draftsman and field engineer from 1923 to 1930. He returned to the employ of the company in 1935 as electrical designer and became research and development engineer in 1941. He is a frequent contributor to technical magazines and a member of Tau Beta Pi. **Manfred Stene** (A '29, M '30) design engineer of the control section, has become electrical engineer. Mr. Stene has been employed by the company since 1924.

Melville Eastham (A '19, M '26) formerly president, General Radio Company, Cambridge, has retired from that position but will continue as a director of the company and for the present will hold the title of chief engineer. Mr. Eastham has been an engineer with the company since 1915. H.

B. Richmond (A '19, F '40) formerly treasurer of the company has been appointed chairman of the board and chairman of the management committee. Mr. Richmond, a 1914 graduate of Massachusetts Institute of Technology, joined the company in 1919. **A. E. Thiessen** (M '41) formerly commercial engineering manager has become vice-president in charge of sales. A 1926 graduate of Johns Hopkins University, Mr. Thiessen was assistant engineer with the Chesapeake and Potomac Telephone Company, Washington, D. C., and member of the technical staff of Bell Telephone Laboratories, Inc., New York, N. Y., before joining the General Radio Company in 1928. He has been commercial engineering manager since 1937.

R. L. Whitney (A '21, M '28) manager of transformer sales, Westinghouse Electric and Manufacturing Company, Sharon, Pa., has been appointed manager of the agency and specialties division of the central district of the company in Pittsburgh, Pa. Mr. Whitney, who first entered the Westinghouse company's power sales department in 1921, has been manager of its Allentown, Pa., office and of its porcelain department in Derry, Pa. **W. W. Sproul, Jr.** (A '42) formerly manager of transformer equipment sales, in Sharon, has been appointed manager of the application department. Mr. Sproul joined the company in 1927 and has been at Sharon in the power transformer sales section and as manager of the equipment section since 1937.

W. G. B. Euler (A '08, M '33) formerly chief engineer, Pacific Coast Gas and Electric Company, San Francisco, Calif., has been appointed vice-president in charge of operations. Mr. Euler was graduated from the University of California in 1905 and was employed by the General Electric Company from 1905 to 1910. In 1910 he joined the Great Western Power Company, San Francisco, and in 1912 was made superintendent of operations. He became general superintendent of the company in 1919. In 1929 when the Pacific Gas and Electric Company absorbed the Great Western company he was made general superintendent of the San Francisco and East Bay divisions of the new company. In 1940 he was appointed chief engineer.

L. J. Moore (A '15, F '42) executive engineer, San Joaquin power division, Pacific Gas and Electric Company, Fresno, Calif., has retired. After three years with the Telluride Power Company, Salt Lake City, Utah, Mr. Moore joined the San Joaquin Light and Power Corporation, Fresno, in 1911 to work on substation maintenance and construction. He became load dispatcher in 1912, engineering assistant to the general superintendent in 1916, electrical engineer in charge of design and construction in 1918, and executive engineer in 1921. Since 1938 when the company was absorbed by the Pacific Gas and Electric Company he has continued as executive engineer of the San Joaquin division.

L. A. Bingham (A '29, M '39) formerly assistant professor in electrical engineering, University of Nebraska, Lincoln, has been appointed associate professor of electrical engineering at the University of Colorado, Boulder. Professor Bingham commenced his teaching career as instructor at Northwestern University, Boston, Mass., from 1924 to 1926. From 1926 to 1929 he was on the staff of the Massachusetts Institute of Technology, Cambridge, and in 1929 was appointed instructor in electrical engineering at the University of Nebraska, becoming assistant professor in 1930. Professor Bingham currently is serving as AIEE vice-president for the North Central District.

C. F. Wagner (A '20, F '40) manager of the central station engineering department of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., recently was honored with the degree of doctor of engineering by the Illinois Institute of Technology for "pioneering research in the application of symmetrical components to power system analyses; for his outstanding contributions to the modern theories of synchronous and induction-machine performance; and for his leadership in the investigation of natural lightning phenomena and the application of knowledge regarding lightning to the protection of electrical systems."

H. E. Strang (A '28, M '39) formerly engineer in the switchgear department, General Electric Company, Philadelphia, Pa., has been named to the staff of the vice-president in charge of engineering design, Schenectady, N. Y. A graduate of Rensselaer Polytechnic Institute, he joined the General Electric Company in 1922. **H. S. Hubbard** (A '23, M '35) of the company's power transformer engineering department, Pittsfield, Mass., has been appointed assistant engineer in the power transformer engineering division and will have charge of design of high-voltage rectifying equipment, testing apparatus, precipitation transformers, and resistance and Sciaky welding transformers.

E. M. Matthews (A '16) engineer, outside plant development department, Bell Telephone Laboratories, Inc., New York, N. Y., has retired. He holds the degrees of bachelor of science (1901) and electrical engineer (1928) from Clemson College. In 1902 Mr. Matthews was employed in the engineering department of the New York Telephone Company, New York, and in 1910 was transferred to the American Telephone and Telegraph Company, New York. In 1919 Mr. Matthews joined the newly formed development and research department and continued with that organization when it was incorporated as Bell Telephone Laboratories in 1925.

R. W. Owens (A '18) formerly general manager of industrial engineering, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., has been made assistant to the president by the Elliott Company, Jeannette, Pa. Mr. Owens, who holds the degrees of bachelor of science and master of science from the University of Illinois, has been connected with the Westinghouse company since 1915. He has held the positions of section engineer, manager of the industrial motor engineering department, general manager of industrial engineering, and manager of the motor division.

Arnold Straussman (A '43) formerly engineer, Long Island Lighting Company, Mineola, N. Y., has become associate editor of *Electric Light and Power* magazine, New York, N. Y. Mr. Straussman has been associated with the power industry since he graduated from Pratt Institute in 1929. With the exception of one year with the Florida Power Corporation, St. Petersburg, he was employed by the Jersey Central Power and Light Company, Sayreville, and Asbury Park, from 1929 to 1940. After a few months with Ebasco Service, Inc., New York, in 1941, he joined the Long Island Lighting Company.

S. H. Mortensen (A '09, F '20) chief electrical engineer, Allis-Chalmers Manufacturing Company, Milwaukee, Wis., recently was awarded the honorary degree of doctor of engineering by the Illinois Institute of Technology for "distinguished leadership in the development of a-c machinery and rectifiers and the extension of their applications; and for his contributions to the design of synchronous-motors and generators and his pioneering research in the development of self-starting synchronous motors and condensers."

W. F. Sims (A '20, F '33) retired chief electrical engineer, Commonwealth Edison Company, Chicago, Ill., recently received the honorary degree of doctor of engineering from the Illinois Institute of Technology for "eminent leadership in the organization, design, and operation of one of the largest electric power generation, transmission, and distribution systems in the world; and for his understanding and stimulation of scientific research in the development and application of equipment for electric power systems."

W. R. Swoish (A '41) formerly vice-president, Roller-Smith Company, Bethlehem, Pa., has been appointed sales manager of the Pennsylvania Transformer Company, Pittsburgh. Mr. Swoish, who was graduated from Ohio State University in 1921, was sales manager of the distribution transformer section and the switchgear division of the Westinghouse Electric and Manufacturing Company, in East Pittsburgh, Pa., and Chicago, Ill., before joining the Roller-Smith Company in 1939.

G. R. Town (A '28, M '37) formerly assistant director of research, Stromberg-Carlson Company, Rochester, N. Y., has been appointed manager of research and engineering. A 1926 graduate of Rensselaer Polytechnic Institute, at which he was instructor from 1933 to 1936, Doctor Town joined the Stromberg-Carlson Company in 1936 as an engineer in the research laboratory. He became engineer in charge of the television laboratory in 1940 and assistant director of research in 1941.

V. A. Sheals (M '39) formerly assistant designing engineer, cable engineering department, General Electric Company, Schenectady, N. Y., has been appointed designing engineer. Associated with the General

Electric company since 1921, Mr. Sheals became a cable engineer in 1923 after completing a student course with the company. In 1930 he was made district cable specialist of the New York, N. Y., office and in 1939 returned to Schenectady as assistant designing engineer.

G. L. Smrz (A '37) formerly vice-president in charge of sales, Line Material Company, Milwaukee, Wis., has been appointed executive vice-president of the company. Born in Milwaukee in 1898, Mr. Smrz joined the Line Material company as manager of the order department in 1919. In 1924 he became secretary-treasurer and general manager of the Line company, East Stroudsburg, Pa. Returning to Milwaukee in 1936 he was made vice-president in charge of sales.

Edward Falck (A '40) formerly deputy director of the Office of War Utilities and recently appointed executive secretary of the Combined Production and Resources Board, has been named director of the OWU. Mr. Falck joined the Office of Production Management in 1941 and has been with the OWU since it was organized. Previously he had been assistant to the vice-president of the Consolidated Edison Company of New York (N. Y.), Inc., and director of research for the Tennessee Valley Authority.

T. F. Peterson (A '25, M '32) formerly director of electric cable engineering and research, American Steel and Wire Company, Cleveland, Ohio, has been appointed manager of the company's newly created electrical sales division. Mr. Peterson has been with the American Steel and Wire Company since 1927 as cable engineer, electrical engineer, director of electric cable works, and since 1941 as director of electric cable engineering and research.

C. L. Keene (A '35, M '38) formerly engineer, mechanical and electrical division, Mutual Boiler Insurance Company, Boston, Mass., has been appointed engineering manager of the company. A 1924 graduate of the Armour Institute of Technology, Mr. Keene served as engineer and supervising engineer for the Ocean Accident and Guarantee Corporation, Ltd., New York, N. Y., before he joined the Mutual company in 1940.

W. D. Coolidge (A '10, M '34) vice-president and director of research, General Electric Company, Schenectady, N. Y., has been awarded one of the two Franklin Medals for 1944 "in recognition of his scientific discoveries, which have profoundly affected the welfare of humanity, especially in the field of the manufacture of ductile tungsten and in the field of improved apparatus for the production and control of X rays."

G. U. Parks (M '30) formerly assistant general manager, Montaup Electric Company, Fall River, Mass., has been made general manager. Mr. Parks was engaged in the electrification of textile mills from 1919 to 1924 and in the latter year joined the Montaup company as system superintendent. He became general superintendent in 1926 and assistant general manager in 1928.

C. A. Hofmeister (A '43) formerly chief electrical engineer Pennsylvania Electric Coil Corporation, Pittsburgh, has been made chief engineer. Born in Pittsburgh in 1909, Mr. Hofmeister received a certificate in electrical engineering from the Carnegie Institute of Technology in 1937. He joined the Pennsylvania Coil company in 1941 as electrical engineer and became chief electrical engineer in 1942.

G. T. Evans (A '27, M '37) formerly assistant chief engineer, the Bristol Company, Waterbury, Conn., has been made manager of production engineering. Mr. Evans entered the employ of the Bristol company in 1928 and after a period in the company's test course, became field engineer in 1930. He was assigned as general staff engineer in 1936 and appointed assistant chief engineer in 1937.

A. D. Robertson (A '39) formerly marine engineer, Allis-Chalmers Manufacturing Company, Milwaukee, Wis., has been appointed assistant manager of the motor division of the company's Norwood, Ohio works. Since he joined the Allis-Chalmers company in 1938, Mr. Robertson has completed the graduate student course in Pittsburgh, Pa., and served as sales engineer in Washington, D. C.

E. J. Herzog (M '43) formerly regional supervisor, Westinghouse Electric International Company, Caracas, Venezuela, has been appointed manager of the company's oil and mining division in New York, N. Y. Mr. Herzog joined the Westinghouse company when he was graduated from the University of Illinois in 1928 and went to Venezuela in 1939.

Roland Whitehurst (A '20, F '43) formerly assistant general sales manager, the Electric Storage Battery Company, Philadelphia, Pa., has been appointed sales manager. Mr. Whitehurst entered the employ of the company in 1908, was manager of its Washington, D. C., branch from 1920 to 1940, and has been assistant sales manager since 1940.

F. G. Logan (A '35) formerly chief development engineer, Ward Leonard Electric Company, Mount Vernon, N. Y., is now manager of development. Mr. Logan joined the company in 1925 as advertising manager, became development engineer in 1929, and was named chief development engineer in 1939.

W. E. Appleton (A '35, M '42) formerly major, Signal Corps, United States Army, now is serving as a lieutenant colonel in Italy.

Wanted: Copies of the January 1944 issue of *Electrical Engineering*. Please mail (parcel post) to American Institute of Electrical Engineers, 33 West 39th Street, New York 18, N. Y., printing your name and address upon the enclosing wrapper. Twenty-five cents plus postage will be paid for each copy returned.

OBITUARY

Matthew Orpheus Troy (A '08, M '12) commercial vice-president, General Electric Company, Schenectady, N. Y., died March 13, 1944. Mr. Troy was born December 15, 1872, in Burlington, N. C., and was graduated from the University of Virginia with the degree of bachelor of science in electrical engineering in 1896. After a short employment as superintendent of a small electric railroad, Charlottesville, Va., he joined the General Electric Company, Schenectady, N. Y., in 1897 and later was transferred to Lynn, Mass., where he was made head of transformer testing and special testing. Appointed assistant to the engineer in charge of the general engineering department in 1899, he became commercial engineer in 1900. From 1902 to 1907 he supervised engineering design in general and in 1908 was named assistant head of the transformer commercial department. In 1910 he was appointed manager of sales, and in 1915 was transferred to Pittsfield, Mass., in that position. Returning to Schenectady in 1923 he was appointed executive assistant manager of the central station department, and became manager of the department in 1928, and commercial vice-president in 1937. In 1935 he also was given supervision of central station commercial engineering. He held several patents and was a member of the National League of Masonic Clubs, the Schenectady Chamber of Commerce, Phi Beta Kappa, and Tau Beta Pi.

Charles Frederic Schoonmaker (A '12) chief engineer, H. J. Heinz Company, Pittsburgh, Pa., died February 20, 1944. Born in Albany, N. Y., November 8, 1887, he was graduated from Pratt Institute of Science and Technology in 1909. In 1910 he entered the testing department of the General Electric Company, Schenectady, N. Y., and in 1917 was made food products specialist for the company in Chicago, Ill. From 1917 to 1921 he was assistant engineer for the Quaker Oats Company, Chicago, Ill., and served as executive engineer for the Iowa Railway and Light Company, Cedar Rapids, from 1921 to 1924, and in 1924 was employed by the Central Hudson Gas and Electric Company, Poughkeepsie, N. Y. He became power engineer for the General Engineering and Management Corporation in New York, N. Y., in 1925 and in Charlottesville, Va., in 1926. He joined the Virginia Public Service Company, Charlottesville, as manager of the power department in 1927, becoming manager of the industrial department in 1928. He was appointed manager of the industrial and rate department of the Seaboard Public Service Company, Alexandria, Va., in 1930 and assistant director of sales for the Columbia Gas and Electric Company, Columbus, Ohio, in 1934. In 1943 he was appointed chief engineer of the Heinz company.

Ernest Schattner (A '06, M '18) consulting engineer, London, England, died February 13, 1944. He was born November 10, 1879, in Berlin, Germany, later becoming a British subject and attending Finabury Technical College. In 1896 he was em-

ployed as technical assistant by the Electrical Power Storage Company, and the London Electric Supply Corporation, both of London. In 1897 he was technical assistant for the Norwich Electricity Works. After his invention of the electricity prepayment meter in 1898 he founded the Schattner Electricity Meter Company, Ltd. As an independent experimentalist he was connected with the General Electric Company, Schenectady, N. Y., from 1902 to 1904 during which time he had several patents issued in his name. Upon his return to England he organized the Electrical Apparatus Company, Ltd., London, of which he became chairman. In 1921 he was made director of the former company and chairman of Electrical Utilities, Ltd., London. He was named consulting engineer in 1929 and retired in 1931 because of illness.

Charles Edward Greene (M '31) consulting engineer, Cleverdon, Varnay and Pike, Winchester, Mass., died March 8, 1944. Mr. Greene, who was born in Boston, Mass., February 8, 1889, was graduated from Massachusetts Institute of Technology with the degree of bachelor of science in mechanical engineering in 1910. He was employed by E. B. Badger and Sons Company, Boston, in 1911 as assistant superintendent of factory and in 1913 was made superintendent. From 1919 to 1926 he had charge of design and installation of equipment manufactured by the company. In 1927 he joined Metcalf and Eddy, Consulting Engineers, Boston, and since 1937 had been associated with Cleverdon, Varnay, and Pike. In 1941 and 1942 he lectured at Smith College and Harvard University. He was awarded the Clemens Herschel prize of the Boston Society of Civil Engineers in 1940 and was a member of the American Society of Mechanical Engineers and the New England Water Works Association. Mr. Greene was the author of several technical papers.

Clyde D. Gray (A '02, M '13, F '20) chief electrical engineer, J. G. White Engineering Corporation, New York, N. Y., died March 29, 1944. Born in Lakeville, N. Y., December 30, 1876, Mr. Gray received from Cornell University the degrees of mechanical engineer in 1900 and master of mechanical engineering in 1901. His entire engineering career was spent in the employ of the J. G. White corporation which he first joined in 1901 as engineering assistant. From 1903 to 1905 he engaged in design, estimating, and correspondence. In 1906 he was made assistant electrical engineer and in 1908 was given responsible charge of all electrical work. He was named assistant electrical engineer in 1909 and chief electrical engineer in 1912. Mr. Gray was a member of the New York Electrical Society, the American Society for Testing Materials, and the National Electric Light Association. He served two terms as president of the village of Pelham, N. Y., was a village trustee for many years, a member of the Board of Education, and a zoning commissioner.

Frederick Herbert Powell (A '08) general manager, Thomas Barlow and Sons, Ltd., Durban, Natal, South Africa, died December 11, 1943. Born September 6, 1883, in Grahamstown, Cape Colony, South Africa, he attended St. Andrew's College and the Transvaal Technical Institute. He was employed as an apprentice by the General Electric Power Company, Ltd., Germiston, Transvaal, South Africa, in 1903, and in 1906 entered the employ of the Crocker Wheeler Company, Ampere, N. J. Returning to South Africa in 1908, he joined the Victoria Falls and Transvaal Power Company, Ltd., Germiston, as assistant construction engineer. He was made acting engineer in charge of the company's compressor station, Fordsburg, Johannesburg, Transvaal, in 1915 and of its Robinson station in 1916. He became resident engineer for the company in 1920. He was associated with Thomas Barlow and Sons first as engineering manager in 1921, was appointed engineering director in 1925 and general manager in 1940.

John Campbell (A '04) consulting engineer, Reading, Mass., died March 6, 1944. He was born in Charlestown, Mass., April 16, 1872. His first electrical work was wiring for the Thomson-Houston Electric Company in 1889. In 1891 he became installation foreman for W. S. Hill and in 1892 operating engineer for the Boston and Maine Railroad. After serving as operating engineer for the United States Navy Department from 1894 to 1901, he established a consulting practice in Chelsea, Mass. He was president and general manager of the Electrical Auditing Company, Boston, Mass., before entering the employ of the Edison Electric Illuminating Company of Boston in 1909 as superintendent of the special service department. Thereafter he remained in that position until he retired from the Boston Edison Company, successor of the Edison Illuminating company, in 1939.

Charles Gardner Winslow (A '02) retired engineer, New York Central Railroad, died in Asheville, N. C., March 9, 1944. Mr. Winslow, who was born August 28, 1871, in Brandon, Vt., was graduated from the University of Vermont with the degrees of bachelor of arts and bachelor of science in electrical engineering. After a brief period as superintendent of construction for the Rochester (Vt.) Electric Light and Power Company and assistant in the office of the engineer, Brooklyn (N. Y.) Rapid Transit Company, Mr. Winslow joined the New York Central Railroad Company about 1904. He was associated with the company first in New York and after 1912 in Detroit, Mich., until he retired in 1938. In 1909 he was connected with Viele, Blackwell, and Buck, New York, N. Y.

John Barnett Edwards (A '29) staff engineer, New York Telephone Company, Brooklyn, died February 5, 1944. Born in Ballinamallard, County Fermanagh, Ireland, January 16, 1898, Mr. Edwards was graduated from St. Luke's College. In 1922 he was employed as engineering assistant by Fothergill Brothers, Exeter, England and from 1923 to 1925 as assistant engineer in the engineering department of the British Post Office, St. Albans, England. Coming to the United States in 1925, he entered the employ of the New York Telephone Company as assistant in the office of the division commercial engineer. In 1928 he was transferred to the plant department where he conducted pre-employment test examinations until 1932. Since 1933 he had been staff engineer.

MEMBERSHIP

Recommended for Transfer

The board of examiners, at its meeting on April 13, 1944, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Alexander, T. W., assistant engr., Bell Telephone Co. of Pa., Pittsburgh, Pa.
Carpenter, C. B., asst. chief engr., Pacific Tel. & Tel. Co., Portland, Ore.
Franklin, C. W., elec. engr., Consolidated Edison Co. of N. Y., Inc., New York.
LeFever, O. L., general supt., Northwestern Electric Co., Portland, Ore.
Stephenson, W. B., area engr., Southwestern Bell Tel. Co., Oklahoma City, Okla.
Titus, O. W., chief engr., Canada Wire & Cable Co. Ltd., Toronto, Ont., Canada.
Tompkins, F. N., associate prof. of elec. engg., Brown University, Providence, R. I.

7 to grade of Fellow

To Grade of Member

Baker, E. W., engr., American Tel. & Tel. Co., New York, N. Y.
Breitwieser, C. J., staff engr., Consolidated-Vultee Aircraft Corp., San Diego, Calif.
Brooks, A. F., president, Southern New England Tel. Co., New Haven, Conn.
Brown, P. A., senior elec. engr., Tacoma City Light Dept., Tacoma, Wash.
Eliason, W. L., elec. engr., The Ontario Paper Co. Ltd., Thorold, Ont., Canada.
Enns, W. E., elec. engr., Portland General Electric Co., Portland, Ore.
Gallagher, Charles, chief engr., Engineering Supply Co. of Australia, Ltd., Brisbane, Australia.
Gordy, T. D., elec. engr., General Electric Co., Pittsfield, Mass.
Grant, A. J., associate engr., National Research Council of Canada, Ottawa, Ont.
Gunther, E. T., branch mgr., General Cable Corp., Houston, Tex.
Hagler, J. M., equipment engr., Southwestern Bell Tel. Co., Dallas, Tex.
Klipsch, P. W., head, technical dept., Southwestern Proving Ground, Hope, Ark.
Logan, J. E., relay engr., Jersey Central Power & Light Co., Allenhurst, N. J.
McLean, C. H., asst. chief engr., Automatic Electric Co., Chicago, Ill.
Middleton, W. J., asst. cable engr., Simplex Wire & Cable Co., Cambridge, Mass.
Mundel, A. B., performance supervisor, Sonotone Corp., Elmsford, N. Y.
Nevins, B. R., senior engr., Philadelphia Electric Co., Philadelphia, Pa.
Newcomb, Theodore, engr. dept., Hartford Electric Light Co., Hartford, Conn.
Partridge, K. L., distribution engr., Hartford Electric Light Co., Hartford, Conn.
Plummer, F. V., asst. to general supt. of production, United Illuminating Co., New Haven, Conn.
Rosing, T. F., engr., Cutler-Hammer, Inc., Milwaukee, Wis.
Sedgwick, A. F., elec. engr., United Illuminating Co., New Haven, Conn.
Thring, R. G., asst. supt. of distribution, Capital Transit Co., Washington, D. C.
Weidelich, D. L., asst. prof. of elec. engg., University of Missouri, Columbia, Mo.
Webber, F. G., research engr., F. W. Sickles Co., Chicopee, Mass.
Werner, H. G., design engr., Department of Public Works, Philadelphia, Pa.
Woodman, F. W., elec. engr., Ontario-Minnesota Pulp and Paper Co., Ltd., Fort Frances and Kenora, Ont., Canada.

27 to grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Names of applicants in the United States and Canada are arranged by geographical District. Any member objecting to the election of any of these candidates should so inform the national secre-

tary before May 31, 1944, or July 31, 1944, if the applicant resides outside of the United States or Canada.

To Grade of Member

Adams, M. D., West. Union Tel. Co., New York, N. Y.
Allen, S. B., Allied Control Co., Inc., New York, N. Y.
Anderson, L. E., Columbus Trans. Co., Columbus, Ga.
Arnold, S. T., Boston Edison Co., Boston, Mass.
Avila, C. F., Boston Edison Co., Boston, Mass.
Bascetta, J. & S Corrugated Paper Mchy. Co., Inc., Brooklyn, N. Y.
Beavers, F. J. (Reelection), Scranton Electric Co., Scranton, Pa.
Berman, A., Imperial Chem. Ind., Ltd., Northwich, England.
Blickley, C. E., Rural Elect. Adm., St. Louis, Mo.
Boucher, C. E., Industrial X-Ray Engrs., Portland, Oreg.
Bray, F., Edward J. White Co., Newark, N. J.
Brehme, F., U. S. Treasury Dept., Washington, D. C.
Burke, A. C. (Reelection), Burke Elec. & X-Ray Co., Ltd., Toronto, Ont., Can.
Chappell, H. D., Burroughs Adding Mach. Co., Detroit, Mich.
Cheney, O. V., Chrysler Corp., Detroit, Mich.
Coates, R. H., Sheffield Corp., Sheffield, England.
Colbath, S., Bibb Mfg. Co., Macon, Ga.
Collier, H. D. (Reelection), Sanderson & Porter, Inc., New York, N. Y.
Correy, S. W., Pub. Serv. Co., Tulsa, Okla.
Crocker, C. F., Otis Elevator Co., Atlanta, Ga.
Dangerfield, H., Rural Elect. Adm., St. Louis, Mo.
Darling, A. G. (Reelection), Gen. Elec. Co., Schenectady, N. Y.
Davis, C. F., U. S. Navy Dept., Portland, Oreg.
Deubel, J. A., Perfex Corp., Milwaukee, Wis.
Downs, G. W., Calif. Inst. of Tech., Pasadena, Calif.
Genachte, P. F. (Reelection), Mexican Lt. & Pr. Co., Ltd., Mexico, D. F., Mex.
Ghigmatti, G., Chattanooga Elec. Pr. Bd., Chattanooga, Tenn.
Happ, E. L., Ecusta Paper Corp., Pisgah Forest, N. C.
Hayden, J. R., Ind. Stacey Corp., Columbus, Ohio
Hill, M. F., Texas-Empire Pipe Line Co., Tulsa, Okla.
Howard, H. P., Jr., Chesapeake & Potomac Tel. Co., Washington, D. C.
Johnson, E. L. (Reelection), Long Island Lighting Co., Roslyn, N. Y.
Johnson, O., Gen. Motors Corp., Detroit, Mich.
Madsen, C. J., West. E. & M. Co., East Pittsburgh, Pa.
Magee, C. F., E. I. du Pont de Nemours & Co., Wilmington, Del.
Miller, E., Allied Control Co., New York, N. Y.
Mills, O. H., Jr., Southwestern Bell Tel. & Tel. Co., Atlanta, Ga.
Montgomery, O. D., West. E. & M. Co., East Pittsburgh, Pa.
Moseley, C. W., R. H. Bouligny, Inc., Charlotte, N. C.
Nelson, N. (Reelection), E. I. du Pont de Nemours & Co., Wilmington, Del.
Pearson, L. E., Rural Elect. Adm., St. Louis, Mo.
Phillips, J. L., J. M. Clayton Co., Atlanta, Ga.
Reap, F. D., Gen. Elec. Co., Pittsburgh, Pa.
Ross, G. F., Koppers United Co., Monaca, Pa.
Rushlow, W. E., Rural Elect. Adm., St. Louis, Mo.
Scott, J. F. (Reelection), Bell Tel. Co. of Pa., Pittsburgh, Pa.
Self, P. N. Cockatoo Docks & Eng. Co., Sydney, Aust.
Sellers, A. A., Koppers United Co., Monaca, Pa.
Sighley, E. N. J. Bell Tel. Co., Newark, N. J.
Smith, D. O. (Reelection), Georgia Pr. Co., Atlanta, Ga.
Smith, M. W., Ohio Edison Co., Akron, Ohio
Stahl, G. D. (Reelection), E. B. Badger & Sons Co., Boston, Mass.
Stebbins, F. G., General Elec. Co., Pittsfield, Mass.
Sywulka, V. S. (Reelection), Cutler-Hammer, Inc., Milwaukee, Wis.
Teeachin, (Reelection), Amer. Gas & Elec. Serv. Corp., New York, N. Y.
Torrence, J. R., Tenn. Valley Auth., Knoxville, Tenn.
Trumbull, A. F., Aeronautical Radio, Inc., Washington, D. C.
Tubbs, L. G. (Reelection), West. E. & M. Co., East Pittsburgh, Pa.
Wakefield, S. J., Assoc. Res., Inc., Chicago, Ill.
White, K. D., White Elec. Const. Co., Atlanta, Ga.
Williams, C. R., West Point Mfg. Co., West Point, Ga.
Willoughby, F. W. (Reelection), E. I. du Pont de Nemours & Co., Wilmington, Del.

62 to grade of Member

To Grade of Associate

United States and Canada

1. North Eastern

Albright, J. W., Gen. Elec. Co., Pittsfield, Mass.
Asmuth, J. L., M.I.T., Cambridge, Mass.
Devine, M. E. C., West. E. & M. Co., New Haven, Conn.
Erickson, E. A., Lieut., U.S.N.R., Syracuse, N. Y.
Eskins, W. E., West. E. & M. Co., Boston, Mass.
Eyles, E. G., General-Elec. Co., Fitchburg, Mass.
Gildersleeve, T. S. (Reelection), Gen. Cable Corp., Boston, Mass.
Hall, T. W., Gen. Elec. Co., Pittsfield, Mass.
Ingram, G. H., Gen. Elec. Co., Syracuse, N. Y.
Kell, R. E., Harvard Univ., Cambridge, Mass.
Krum, C., Cent. Hud. Gas & Elec. Corp., Poughkeepsie, N. Y.
Macpherson, J. F., Gen. Elec. Co., Lynn, Mass.
Mansur, R. L., West. E. & M. Co., Boston, Mass.
Miller, G. A., Post & Lester Co., Hartford, Conn.
Nickels, J. M., Gen. Elec. Co., Schenectady, N. Y.
Peterson, J., Gen. Elec. Co., Lynn, Mass.
Prince, L. W., Bethlehem Steel Co., Boston, Mass.
Rice, B. S., Niag. Hudson System, Buffalo, N. Y.
Simmons, H. O., Jr., Gen. Elec. Co., Lynn, Mass.
Southwell, L. H., West. E. & M. Co., South Boston, Mass.
Sprague, M. B., So. New Eng. Tel. Co., New Haven, Conn.
Taber, J. H., Int'l. Bus. Mach., Rochester, N. Y.

2. Middle Eastern

Alderson, W. S., Ensign, U.S.N.R., Washington, D. C.
Benet, F. W., Arthur G. McKee & Co., Cleveland, Ohio
Bogart, L. J., Naval Ord. Lab., Washington, D. C.
Carroll, B. E., Glenn L. Martin Co., Baltimore, Md.
Cheshire, W. F., Cincinnati Gas & Elec. Co., Cincinnati, Ohio
Delmege, A. H., Ensign, U.S.N.R., Washington, D. C.
Gittings, W. N. (Reelection), Gen. Elec. Co., Philadelphia, Pa.
Grantham, J. O., Naval Res. Lab., Washington, D. C.
Jay, J. H., Wright Field, Dayton, Ohio
Kindt, F. T., U. S. Navy Yard, Phila., Pa.
Lee, R. West, E. & M. Co., Baltimore, Md.
Mead, O. J., Naval Res. Lab., Washington, D. C.
Myers, S. D., U. S. Army, Akron, Ohio
Norton, J. M., Naval Ord. Lab., Washington, D. C.
Pearson, E., Leeds & Northrup Co., Philadelphia, Pa.
Peters, C. C., Captain, U. S. Army, Washington, D. C.
Robenalt, W. T., Hazel Atlas Glass Co., Zanesville, Ohio
Roberts, N. J., Ohio Pub. Serv. Co., Warren, Ohio
Rose, D. J., Firestone Tire & Rubber Co., Akron, Ohio
Schenck, P. C., U. S. Engineers, Dayton, Ohio
Smith, F. G., Jr., Naval Res. Lab., Washington, D. C.
Steinlauf, B., City Eng. Co., Dayton, Ohio
Taylor, C. L., Jr., Keebler Weyl Baking Co., Philadelphia, Pa.
Wagner, M. J., Kelso-Wagner Co., Dayton, Ohio
Whalen, W. T., Alum. Co. of America, Burlington, N. J.
Wilson, W. West. E. & M. Co., Lester, Pa.
Woloszynek, B. M., Linderme Tube Co., Cleveland, Ohio
Wright, H. N., Naval Ord. Lab., Washington, D. C.

3. New York City

Anderson, L. H., Heyden Chem. Corp., Fords, N. J.
Beck, W. S., Westinghouse Elec. Int'l Co., New York, N. Y.
Beckmeyer, J. W., Fed. Tel. & Radio Corp., East Newark, N. J.
Brand, A. C., Cox & Stevens, Inc., New York, N. Y.
Brown, H. E., Penna. R.R. Co., New York, N. Y.
Buchwald, H., West. Union Tel. Co., New York, N. Y.
Cambria, W., Brewster Aero. Corp., Long Island City, N. Y.
Cannon, J. F., Bell Tel. Labs., New York, N. Y.
Convery, J. F., Jr., Gibbs & Cox, Inc., New York, N. Y.
Cozzie, J. A., U. S. Navy Yard, Brooklyn, N. Y.
Furman, S. P., U. S. Navy Yard, Brooklyn, N. Y.
Gardner, W. E., Fed. Tel. & Radio Corp., Newark, N. J.
Hoagland, K. A., Allen B. DuMont Labs., Inc., Passaic, N. J.
Minc, A., Columbia Univ., New York, N. Y.
Morrison, W. J., Prudential Ins. Co., Newark, N. J.
Nagata, B. Y., Fed. Tel. & Radio Corp., East Newark, N. J.
Reed, R. A., Fed. Tel. & Radio Corp., East Newark, N. J.
Rouquette, H. P., U. S. Navy Yard, Brooklyn, N. Y.
Smith, G. V. (Reelection), Fed. Tel. & Radio Corp., Newark, N. J.
Sparkman, J. J., Westinghouse Int'l Co., New York, N. Y.
Stone, C. E., Jr., Bell Tel. Labs., Inc., New York, N. Y.
Voss, C. W., Givaudan-Delawanna, Inc., Clifton, N. J.
Waffner, W. J., W. L. Maxson Corp., New York, N. Y.

4. Southern

Byck, S. M., Byck Elec. Co., Inc., Savannah, Ga.
Camus, F. G., City of Shreveport, Shreveport, La.
Cunningham, J. W., Clinton Engr. Works, Oak Ridge, Tenn.
Dycus, H., Knoxville Electric Pr. & Water Bd., Knoxville, Tenn.
Fishburn, R. E., Royal Indemnity Co., Atlanta, Ga.
Francisco, C. E., Carroll County Elec. Dept., McKenzie, Tenn.
Gostin, B. F. (Reelection), Tenn. Valley Auth., Chattanooga, Tenn.
Harden, W. F., Georgia Pr. Co., Columbus, Ga.
Hine, R. T., Tenn. Eastman Corp., Kingsport, Tenn.
Jones, P. F., Jr., Georgia Pr. Co., Atlanta, Ga.
Long, J. T., Clemson College, Clemson, S. C.
Martin, B. H., Tenn. Valley Auth., Chattanooga, Tenn.
May, W. O., Light Gas & Water Div., Memphis, Tenn.
Morrison, R. S., West. E. & M. Co., Birmingham, Ala.
Moyer, G. E., Elec. Const., Inc., Pascagoula, Miss.
Nees, J. G., Eckardt-Nees Electric Co., Atlanta, Ga.
Pollock, W. J., Jr., Tenn. Eastman Corp., Oak Ridge, Tenn.
Raney, J. R., Georgia Pr. Co., Atlanta, Ga.
Schimmel, H. C., Hickman Fulton Rural Elec. Co-op., Hickman, Ky.
Weaver, C. H., Tenn. Eastman Corp., Oak Ridge, Tenn.

5. Great Lakes

Barnes, H. A., City Police Div., Flint, Mich.
Bergrun, T., Midland Elec. Coal Corp., Farmington, Ill.
Boesenwetter, C. C., Goodman Mfg. Co., Chicago, Ill.
Bollinger, W. H., Esterline-Angus Co., Indianapolis, Ind.
Brown, R. P., Delta-Star Elec. Co., Chicago, Ill.
Buckley, A. W., White City Elec. Co., Chicago, Ill.
Clodfelter, N., American Tel. & Tel. Co., Indianapolis, Ind.
Corrigan, R. E., Dodge, Chicago Plant, Chicago, Ill.
Crumpton, J. T., Amer. Tel. & Tel. Co., Indianapolis, Ind.
Dischinger, I. E., Jr., Aluminum Co. of America, Brookfield, Ill.
Dolinko, L., Illinois Inst. of Tech., Chicago, Ill.
Easterday, V. I., Northern Ind. Pub. Serv. Co., Hammond, Ind.
Ewald, S. J., Jr., American Tel. & Tel. Co., Chicago, Ill.
Gall, J., Esterline-Angus Co., Inc., Indianapolis, Ind.
Gould, H. A., Dodge Chicago Plant, Chicago, Ill.
Grennan, C. E., Dodge Chicago Plant, Chicago, Ill.
Koch, L., Chrysler Corp., Chicago, Ill.
Koenig, M. F., Cutler-Hammer, Inc., Milwaukee, Wis.
Martin, J. E., Dodge Chicago Plant, Chicago, Ill.
McCarvell, J., Emerson Comstock, Chicago, Ill.
Meining, R., EaCello Corp., Detroit, Mich.
Moore, B. T., Gen. Elec. Co., Chicago, Ill.
Petersen, V. R., Gen. Elec. Co., Fort Wayne, Ind.
Schwartzburg, W. E., Allis-Chalmers Mfg. Co., West Allis, Wis.
Sears, J. W., Ind. Bell Tel. Co., Indianapolis, Ind.
Seidenfeld, B. A., Dodge Chicago Plant, Chicago, Ill.
Spankie, T. S., Dodge Chicago Plant, Chicago, Ill.
Thompson, D. L., Northern Ind. Pub. Serv. Co., Hammond, Ind.
Tracht, P. A., Evans Prods. Co., Detroit, Mich.
Troup, R. J., Northern Ind. Pub. Serv. Co., Hammond, Ind.
Walters, R. E., Allen-Bradley Co., Milwaukee, Wis.
Wessel, R. A., Dodge Chicago Plant, Chicago, Ill.
Wolff, A. J., Dodge Chicago Plant, Chicago, Ill.

6. North Central

Cross, W. D., Univ. of Colo., Boulder, Colo.

7. South West

Cox, W. H., Consolidated Steel Corp., Ltd., Orange Texas
Croy, R. J., Pratt & Whitney Aircraft Corp., Kansas City, Mo.
Floyd, C. B., Southwestern Prov. Ground, Hope, Ark.
Green, C. A., Curtis-Wright Corp., St. Louis, Mo.
Holden, H., Jr., Southwestern Bell Tel. Co., Houston, Texas
Horak, R. K., Curtiss-Wright Corp., St. Louis, Mo.
Merchant, M. W., Rural Elec. Adm., Abilene, Texas
Sandford, E. O., Jr., Sandford Const. Co., Oklahoma City, Okla.
Wooldridge, K. E., Alum. Ore Co., Bauxite, Ark.

8. Pacific

Beren, W. J., Capitol Elec. Co., San Diego, Calif.
Bertrand, D. C., Gen. Elec. Supply Corp., San Diego, Calif.
Brackett, P. E., Line Material Co., Los Angeles, Calif.
Chapman, H. B., Electrical Contractor, Los Angeles, Calif.
Dusenbery, H. S. (Reelection), Moore Dry Dock Co., Oakland, Calif.
Gooder, P. O., Fischbach & Moore, Inc., Richmond, Calif.
Herstedt, A. H., U. S. Navy Yard, Mare Island, Calif.
Kenworth, W., Littlefuse, Inc., El Monte, Calif.
Kilman, L. B., Jr., Hughes Aircraft Co., Los Angeles, Calif.
Larimore, E. A., Douglas Aircraft, Inc., Santa Monica, Calif.
Leach, F. C., Dept. of Water & Pr., Los Angeles, Calif.
Ryals, C. A., Jr., Ensign, U.S.N.R., San Francisco, Calif.
Schulz, E. B. (Reelection), Lockheed Aircraft Corp., Burbank, Calif.
Skow, H. N., West. E. & M. Co., San Francisco, Calif.
Thedaker, G. R., Jr., Public Serv. Dept., Burbank, Calif.

9. North West

Boyd, H. L., Jr., Lieut., U. S. Army, Seaattle, Wash.
Fox, J. D., Alum. Co. of America, Trentwood, Wash.
Groth, S., U. S. Engineers, Portland, Oreg.
Mitchum, C. D., Associated Shipbuilding Corp., Seattle, Wash.
Short, H. A., J. J. Agutter & Co., Seattle, Wash.
Stobie, J., Wash. Water Pr. Corp., Spokane, Wash.

10. Canada

Elliott, A. H., Can. West. Co., Ltd., Hamilton, Ont., Can.
Ham, J. M., Univ. of Toronto, Toronto, Ont., Can.

Elsewhere

Alfaro, G. B., Mexican Lt. & Pr. Co., Mexico, D. F., Mex.
Beach, J. E., Trinidad Leaseholds, Ltd., Trinidad, B. W. I.
Clark, L. J., British Thomson-Houston Co., Ltd., Rugby, England
Espriella Miranda, F., Mexican Lt. & Pr. Co., Ltd., Mexico, D. F., Mex.
Gomez, R. N., Mexican Lt. & Pr. Co., Ltd., Mexico, D. F., Mex.
Higgins, B. G., British Thomson-Houston Co., Ltd., Rugby, England
Medinillo Valencia, E., Mexican Lt. & Pr. Co., Ltd., Mexico, D. F., Mex.
Pamnani, L. C., Fazilka Elec. Supply Co., Ltd., Fazilka, Punjab, India
Villada, J. N., Ocrotlcca Mexicanos, Mexico, D. F., Mex.
Wheatley, M., Mexican Lt. & Pr. Co., Ltd., Mexico, D. F., Mex.

Total to grade of Associate

United States and Canada 159

Elsewhere 10

OF CURRENT INTEREST

British–American Pact Lifts Patent Restrictions

The pooling of scientific and technical information and of patent rights accomplished by means of the British–American Patent Interchange Agreement effective January 1, 1942, particularly has benefited aircraft, radio, and ordnance production according to a recent statement of the War Department.

Confined to the manufacturing of products required in winning the war, the agreement grants American manufacturers free licenses to use British-owned patents and extends the same privileges to British manufacturers who wish to employ American-owned patented devices or ideas. According to the agreement processes, technical information, drawings, designs, and patent rights owned by the manufacturers of one nation are released to the other. At the end of the war patent rights will revert to their respective owners, and property interests in the postwar use of all kinds of industrial information are being safeguarded by provisions of the Lend-Lease Act.

Among the products being manufactured in both the United Kingdom and the United States under the terms of the agreement are: a kite which carries aloft an aerial for radioing distress signals; air compressors; range finders; illuminated gun sights; turrets; fuses; incendiary bombs; air-borne lifeboats; lathes; bomb releases; catalysts; torpedoes; condenser tubes; warship propellers; periscopes; bearings; and lacquers. Many of the products affected may not be publicized during the war.

Government contractors wishing to exercise these wartime rights should file a request through the contracting officer or technical representative of the agency with which they have war contracts. A requisition is prepared by the agency and forwarded to the British representatives. Inasmuch as the British Government has broad powers under the Patents and Designs Act, the information and licenses can be forwarded promptly. Regulations under which lend-lease aid can be obtained from the United Kingdom and several other Allies are set forth in War Department procurement regulations and Navy procurement directives. Copies of the Patent Interchange Agreement and other lend-lease and reciprocal-aid agreements will be supplied upon request by the State Department, Washington 25, D. C.

War Safety Tests Lead Year's Work at Underwriters' Laboratories

The current work of Underwriters' Laboratories, Inc., to reduce fires, accidents, and crime, and reports of the activities of the various engineering departments for 1943 took precedence over celebration of the organization's 50th anniversary at the annual dinner meeting, April 6 in Chicago, Ill. John C. Harding, chairman of the board of trustees, presided.

President Alvah Small (M '37) recalled briefly the history of the development of the Laboratories and then outlined the highspots of the year's achievements. Besides their great contributions to the war effort he noted a growing number of conferences with manufacturers indicating increased activity in postwar planning for the production of civilian goods. Included in the reports of the departmental laboratories' heads were some of interest to electrical engineers.

Robert B. Shepard (F '36), chief electrical engineer, whose headquarters are at the New York City, N. Y., testing station, reported that the critical status of steel, copper, zinc, and rubber had made necessary the testing of many new designs of electrical equipment. A variety of new synthetic insulations for electric wires has been investigated, some of which have revealed properties superior to those of natural rubber, he stated.

The shortage of steel for construction has given an impetus to the development of new methods of flameproofing lumber, and several surface-treatment and impregnation methods have been found effective, according to Albert J. Steiner, engineer of the fire-protection department. Another new development is in nonmetallic heating and air-conditioning ducts. Tests show that certain of these are so constructed that they provide adequate insulation and strength and do not introduce a fire hazard.

Earl J. Smith, engineer of the gases and oil department, reported that many tests had been conducted on oil-fired heating and power equipment and on acetylene generators for war projects.

R. W. Hendricks, hydraulic engineer, loaned to the United States Rubber Reserve Company to direct an investigation at Baytown, Tex., told of large-scale tests run there to determine ways of protecting butadiene and styrene storage tanks against fire. Fifty to 125 gallons of gasoline a minute were allowed to burn for several hours at a time in order to study the prevention and control of these fire explosions.

H. C. Conick, United States manager of Royal Insurance Company, Ltd., New York, N. Y., was the only new trustee elected at the annual meeting.

Army Training Reserve to Be Operating by July 1

Approximately 150,000 from an estimated 200,000 young men who will be graduated from high school in June 1944 took the qualifying examination for admittance to the Army Specialized Training Reserve, substitute for the Army Specialized Training Program which was curtailed because of military necessity.

The new program, which has been expanded to concur with the suggestions of the American Council on Education's committee on the relationships of higher education to the Federal Government, admits high school graduates between the ages of 17 years and 17 years and nine months and a limited number between 17 years and nine months and 22 years of age who have completed basic military training. Men between 17 and 19 years of age, inclusive, who are high school graduates by July 1, 1944, may express a preference for the V-12 program of the Navy.

Those who are accepted from the first age group are assured of a minimum of nine months of college work, and the cost of tuition, fees, food, housing, and medical care will be paid by the Government. Men will be assigned to curricula in applied sciences; chemical, and biological sciences preparatory to medical and dental studies; and mathematics and physics. These curricula are similar to previous ASTP curricula.

Many details concerning the assignment of applicants to particular colleges and universities, the duration of the program for various age groups, and specific curricula available will be worked out before July 1.

Technical Advisory Committee Classifies Alien Patents

The technical advisory service recently set up within the Smaller War Plants Corporation (*EE, Nov '43, p 512*) has undertaken to sift from the 45,000 foreign patents vested in the Alien Property Custodian, those potentially most valuable to small manufacturers. The patents selected will be analyzed by science advisory committees and the most promising subjected to further study. Bulletins listing and classifying the final selections will be made available to small manufacturers through the Corporation's offices.

Patents which were not exclusively licensed to American firms or citizens before seizure of the patents by the Government are available immediately to those interested. Licenses on enemy patents are nonexclusive, nonassignable, and royalty-free, and the license applications fee is $15 per patent. Small plants will be notified of the date of the bulletins publication. Meanwhile a detailed catalogue of all vested patents may be consulted in each of the regional and field offices of the Smaller War Plants Corporation.

Aircraft Electrical Council Formed by NEMA. A subdivision of the National Electrical Manufacturers Association, the Aircraft Electrical Council, which will function as a liason group between the aircraft and electrical manufacturing industries was organized with 50 member companies at the spring meeting of the NEMA in Chicago, Ill. The Council will make available the experience and facilities of electrical manufacturers to producers of aircraft and representatives of the armed services confronted with aviation problems. Member companies will be provided with information abou' performance and production requirements of electric equipment for aircraft applications, and per-

tinent purchase specifications will be developed. The aircraft industry and its affiliated professional and technical organizations may consult with the Council on any of its problems pertaining to the development and procurement of electrical products. The Council's offices are at 155 East 44th Street, New York 17, N. Y.

Device Saves Drafting Time and Materials. Primarily to offset the shortage of draftsmen, a device for judging whether a completed drawing will reproduce satisfactorily, known as the Legimeter, has been developed by D. J. Wishart of The Glenn L. Martin Company, Baltimore, Md. The device is a two-panel illuminated table. In one panel are sample drawings from which satisfactory prints have been made. The second panel is a sheet of ground glass on which the draftsman can place the drawing to be evaluated. With both panels illuminated by light of the same intensity, a moment's scrutiny will reveal whether the lines of the drawing are heavy enough for satisfactory reproduction.

ANEPA to Be Disbanded. Because of changes in the electronics production program and the functions of the field services of the Army, Navy, and War Production Board, the Army–Navy Electronics Production Agency will be dissolved within the next 60 or 90 days. Its duties and staff will be distributed between the Signal Corps procurement division, the Navy Bureau of Ships, and the WPB radio and radar division. Some of the ANEPA headquarters and field staff will be transferred to the other agencies.

POSTWAR • • • • •

CED Handbook on Postwar Outlook for Business Issued

"Planning the Future of Your Business," a handbook prepared for the Committee for Economic Development by a special committee of the Association of Consulting Management Engineers, has been issued by CED headquarters in New York, N. Y. The handbook, which can be obtained only through the local Committees for Economic Development now organized in approximately 1,408 communities throughout the United States, offers concrete suggestions that may be adopted by industrial employers in planning their postwar production and employment programs. In brief, these are:

1. To define and allocate responsibility for postwar planning.
2. To plan respective product programs.
3. To plan corresponding market and sales programs.
4. To determine the manufacturing facilities required.
5. To estimate employment requirements, define jobs, and plan employee training.
6. To estimate the operating funds needed and to plan their sources.

The Committee for Economic Development is a nonprofit organization established to assist, within communities, company-by-company planning for new high levels of production, employment, and distribution in the postwar period. It is self-supporting, being financed entirely by contributions from private business. Eighteen trustees, 12 regional chairmen, and approximately 100 district chairmen comprise its administrative board and determine its national policies. The idea of establishing the Committee originated when Secretary of Commerce Jesse Jones called together a group of business men in 1942; as formally organized a year later, it is independent of Government subsidy and control, but has been assured co-operation by governmental agencies as well as by great national business organizations.

Basic responsibility for the Committee's activities rests with its board of trustees, under the chairmanship of Paul G. Hoffman, president, The Studebaker Corporation, South Bend, Ind. Its efforts are carried out through two major divisions—the field development division and the research division.

The field development division, headed by Marion Folsom, treasurer of Eastman Kodak Company, Rochester, N. Y., is responsible for stimulating, encouraging, and helping individual enterprises to plan their product and marketing programs for the postwar periods. Its efforts are directed at reaching and influencing the many smaller businesses and the limited group of large employers equally. Assisting the division is an industrial advisory board, composed of men highly trained in the knowledge of the development of new materials and new technologies, under the chairmanship of David C. Prince (F '26) vice-president in charge of application engineering, General Electric Company, Schenectady, N. Y.

The research division, under the chairmanship of Ralph Flanders, president of Jones and Lamson Machine Company, Springfield, Vt., is engaged in studies, national in scope, concerned with the practical problems of reconversion to civilian production and with the defining of conditions necessary to encourage progresive growth of business enterprise in the postwar period. The studies are undertaken by a research committee of business men who are advised by a board of outstanding economists and social scientists. Professor Sumner Slichter, Lamont professor of economics, Harvard University, Cambridge, Mass., presides over the board, assisted by Robert DeB. Calkins, Dean of the School of Business, Columbia University, New York, N. Y. Professor Theodore Yntema, professor of economics on leave from the University of Chicago, Ill., is engaged as full-time research director.

Association for an International Office for Education Formed

Formation of the American Association for an International Office for Education, under the chairmanship of Doctor Harlow Shapley, Harvard College Observatory, was announced recently. Comprised of nationally known educators, industrialists, church leaders, labor leaders, and authors, the association is working to enlist the support of the American public in the establishment of such an internationally recognized office, which will insure that education be given proper ranking with political organization, police, distribution of raw materials, stabilization of currencies, and improving of health conditions in postwar planning programs.

Among the educational and intercultural benefits that an international education office can effect are the recommendation of minimum standards at all educational levels; supervision of the distribution of funds to repair devastated school systems and universities, if the United Nations determine upon a policy of relief and rehabilitation of schools; assistance to the nations through adult education to meet the problems of adjusting demobilized armed forces and people in war industries, and in the resettlement of refugees; establishment of a center for the exchange of experiences and techniques in the field of education and cultural relations; facilitation of the international exchange of students, professors, scientists, and artists; and establishment of schools for administrators and teachers to train personnel for those countries which, after the war, will be staffed inadequately and which, at first, will not be able to provide such facilities themselves.

Projected Station at Olney to Lead Postwar FM Broadcasting Research

Application for the licensing of a unique type of FM broadcasting station to be located in the Washington, D. C., area has been filed with the Federal Communications Commission in the name of the FM Development Foundation. Organized by Edwin H. Armstrong, inventor of the FM system, and by C. M. Jansky, Jr. (M '32) and Stuart L. Bailey, members of the consulting engineering firm of Jansky and Bailey, Washington, who constructed the first FM station in that city, the Foundation will carry on research and experimentation to foster the development of the FM broadcasting art.

The removal of the FCC's ban on newspaper ownership of stations, and the gradual realization by various educational groups and institutions of the possibilities opened up by this new method of broadcasting has produced an enormous quantity of applications for licenses that are beyond the resources of the short-handed Washington engineering firms to handle. With the granting of these applications and the widespread postwar propagation of FM stations throughout the United States, many new problems of allocation and operation will arise, which the Foundation has set itself to solve.

Proposed site for the station is Olney, Md., because of its convenience to the Jansky and Bailey laboratories, which will supervise the tests, and because its service over the capital area and surrounding territory of approximately 20,000 square miles will be an effective demonstration of the possibilities of of the system. The transmitting equipment will be substantially a duplicate of Professor Armstrong's original staticless station at Alpine, N. J. Construction of the station, a project estimated at six to nine months, is pending favorable action by the Commission and the end of the war.

RMA Studies Postwar Employment and Contract Termination. An industry survey on postwar employment recently was authorized by the board of directors of the Radio Manufacturers Association. From the brief questionnaire which will be forwarded to manufacturers shortly, estimates on postwar employment, for both present and new employees, will be developed. Statistics on both men and women workers who probably will retain their present positions and also on former employees now in the armed services is desired. Comparative data for 1940 will be used in arranging the material received. A subcommittee to present RMA recommendations on termination procedure to government officials has been appointed by the contract terminations committee which has endorsed the horizontal company settlements plan devised by the Baruch agency. Members of the subcommittee are R. F. Sparrow, J. P. Rogers, L. W. Adkins, M. F. Balcom, and R. C. Sprague.

Bacon Foresees Unparalleled Postwar Prosperity. "Postwar prosperity in the United States, if not the world, will far exceed, during its first quarter of a century, any business activity for a like period the world has ever witnessed," in the opinion of G. W. Bacon, chairman of the board and a founder of Ford, Bacon, and Davis, Inc., New York, N. Y. Speaking at the 50th anniversary celebration of his company recently, Mr. Bacon outlined the probable industrial trends of the next 50 years and reviewed the history of the engineering firm he had helped found. A commemorative medal was presented to Mr. Bacon by James F. Towers, president of the firm on behalf of his associates. Mr. Bacon expects stimulation for postwar prosperity to come from the almost total depletion of normal inventories. New markets will result "from existing and expanding incomes, living standards and credit facilities," he said. He valued postwar production and distribution at tens of billions of dollars and predicted "credit facilities such as our people have never known" to supply the vast sums for replenishing "present enormous volumes of depreciated facilities and equipment of all kinds in the United States and beyond our borders." Mr. Bacon maintained that the primary task of the industrial world for the next half century would be to insure raw material bases natural and synthetic, continuing to meet the world's requirements.

INDUSTRY

40 Per Cent Decline in Industrial Accidents Is Goal for 1944

One million fewer work accidents in the next 12 months is the goal set by Secretary of Labor Frances Perkins for attainment by American labor and management, according to Verne A. Zimmer, director of labor standards, United States Department of Labor.

The new goal would be a 40 per cent decline from the 2,500,000 industrial accidents that occurred in 1943—the highest total in history, Mr. Zimmer explained. Analyzing the statistics further he pointed out that 18,400 workers had been killed, 1,700 more had been totally and permanently disabled, 108,000 others had been permanently crippled, and that accidents temporarily had removed from service 2,225,000 workers for an average of 15 days apiece.

In the past three years, to reduce the number of accidents in industry 600 top-flight safety engineers, recruited by the Department of Labor on a voluntary basis, have brought safety service directly into 25,000 war-contract plants. Of the firms accepting this service, 75 per cent have reduced their accident frequency materially, and many of the plants report one, two, or three years without a single lost-time injury.

In addition to this Government aid the Department of Labor and the Office of Education have been sponsoring safety-training courses for labor in which 50,000 plant foremen and leadmen already have received practical instructions on how to make a plant accident-free. Detailed information concerning these special training courses for labor groups can be obtained by writing to the division of labor standards, United States Department of Labor.

Railroads and Telegraph Companies to Honor Morse

The 100th anniversary of the sending of the first telegraph message, "What hath God wrought!" by Samuel Morse is being observed on May 24 by the telegraph industry and the Association of American Railroads with the re-enactment in Washington, D. C., and Baltimore, Md., of the first ceremony.

The original message was flashed over the first telegraph line from the chamber of the United States Supreme Court, then in the Capitol in Washington, to the Baltimore and Ohio Railroad station in Baltimore on May 24, 1844. In addition to the re-enactment of that event, the centennial will be celebrated by the unveiling of a memorial plaque by a joint Congressional committee. The telegraph companies participating in the ceremony will be the Western Union Telegraph Company, the International Telephone and Telegraph Corporation, Radio Corporation of America Communications, Inc., and the American Telephone and Telegraph Company.

A commemorative symposium on the Morse telegraph is being planned for the AIEE summer meeting in St. Louis, Mo., June 26–30, 1944.

Powerful Projector Contacts Cloud Ceiling

Westinghouse photo

This 16-inch searchlight and alidade, an instrument which sights the projector's beam, are placed 1,000 feet apart on the roofs of aircraft hangars to determine the altitude of the cloud ceiling. The searchlight's beam, which can reach five miles high, in striking the lowest layer of clouds forms a round bright spot about the size of a dinner plate. This spot is sighted through the telescope-like tube of the alidade and focused in the center of a mirror at its base. The tube swings across a semicircular strip of steel marked off for hundreds and thousands of feet. When the tube is focused, a marker at one end indicates the altitude of the clouds.

OTHER SOCIETIES

Wickenden's "The Second Mile" Republished by ECPD

A new version of "The Second Mile," an address delivered before the Engineering Institute of Canada in February 1941 by William E. Wickenden (F '39) AIEE vice-president and president of the Case School of

Applied Science, Cleveland, Ohio, has been reissued by The Engineers' Council for Professional Development under the title, "The Second Mile—A Resurvey, 1944." Essential substance of the original address appeared in *Electrical Engineering*, May 1942, pages 242–7.

The revised pamphlet is slanted toward presenting the engineering profession to the young engineer. To this end the text was shortened, the style modified, and a new section, "Does an Engineer Need His Profession?" was added. Copies of the revised reprint can be obtained at 10 cents per single pamphlet, five cents per pamphlet in small lots, and $3 per hundred, from the ECPD, 29 West 39th St., New York 18, N. Y.

Future Meetings of Other Societies

American Society of Mechanical Engineers. Semi-annual meeting, June 19–20, 1944, Pittsburgh, Pa.

American Society of Refrigerating Engineers. 31st spring meeting, June 5–7, 1944, Pittsburgh, Pa.

Canadian Electrical Association. Annual meeting, June 22–23, 1944, Murray Bay, Que.

Edison Electric Institute. Annual conference, June 6–7, 1944, New York, N. Y.

Radio Manufacturers Association, 20th annual convention, June 6–7, 1944, Chicago, Ill.

Society for the Promotion of Engineering Education. Annual meeting, June 25–28, 1944, Cincinnati, Ohio.

IRE Publishes Facsimile Standards. Results of study by the 1942 and 1943 committee on facsimile of the Institute of Radio Engineers recently have been published as "Standards on Facsimile: Temporary Test Standards." The standards were compiled to satisfy urgent demands from IRE members, the Armed Forces, and the radio industry as a whole, ensuing from their respective war requirements. The standards cover fundamentals of facsimile, apparatus performance, and transmission. Experience in applying the standards and subsequent review by facsimile technical committees will make possible their future publication in more complete and carefully considered form. The standards may be procured from the IRE, 330 West 42nd Street, New York 18, N. Y., at 20 cents per copy.

LETTERS TO THE EDITOR

INSTITUTE members and subscribers are invited to contribute to these columns expressions of opinion dealing with published articles, technical papers, or other subjects of general professional interest. While endeavoring to publish as many letters as possible, Electrical Engineering reserves the right to publish them in whole or in part or to reject them entirely. Statements in letters are expressly understood to be made by the writers. Publication here in no wise constitutes endorsement or recognition by the AIEE. All letters submitted for publication should be typewritten, double-spaced, not carbon copies. Any illustrations should be submitted in duplicate, one copy an inked drawing without lettering, the other lettered. Captions should be supplied for all illustrations.

A Letter on the Kilgore Bill

This letter from an AIEE member to H. M. Kilgore, United States Senator, supplements Doctor Bush's letter published in the February 1944 issue of "Electrical Engineering," pages 57–62.

Dear Senator Kilgore:

Since I received the testimony on the science mobilization bill, S 702, which you sent me, I have given much study to the subject and, as a result, I send you herewith my conclusions.

Considerations of the bill may be divided into three parts:

1. General political implications.
2. The fostering of science in educational institutions.
3. Scientific developments in relation to industry.

GENERAL POLITICAL IMPLICATIONS

There seem to be two fairly well-defined schools of thought the one advocating a strong paternalistic Federal Government probably based on the ideas of efficiency and the general welfare, and the other advocating the rights of the individual in a free democracy.

Possibly those who belong, more or less consciously, to the first school at the same time consider themselves allied to the second. The president of a weak college, seeing an opportunity to secure Federal aid, might favor the bill although he would at the same time assert his devotion to the ideals of democracy and the freedom of the individual.

There can be no doubt that Americans in overwhelming majority wish to preserve our Government in its traditional form and oppose the tendency, toward an all-powerful state. This bill, then, should be written so as in no way to infringe on the freedom of the people. Some of your own comment indicates that you may believe the bill as drafted is satisfactory in this regard and, if so, you will not be averse to having it tested by competent and unprejudiced persons. For my part, I believe it has grave faults in that it gives the administrator powers of coercion which should rest with Congress.

Another political implication is bound up with the organization as planned. The plan is that most groups should be represented in shaping the policy of the Office of Science Mobilization regardless of their qualifications, experience, or interest in, scientific research and development.

To obtain this general representation the Office includes, besides the all-powerful administrator, a board, and a committee. The board of seven, including the administrator, contains only two members who are scientists or technologists, the other four representing different sections of American life. The six members are entirely subservient to the administrator with the exceptions that "they shall have access to all information of the Office relating to the administration thereof," and the board must approve compensation, determined by the administrator, to persons as a reward for inventions or discoveries deemed by the administrator to be in the national interest and when they are vested in the Office.

The committee consists of the board, single representatives of Federal departments, four additional representatives of the consuming public, making five in all, six additional representatives of labor, making seven in all, six additional representatives of management (including small business), making seven in all. The committee thus consists of 24, plus as many Federal department representatives as the President shall choose to appoint, of whom only five need be scientists or technologists. The function of the committee is to advise and consult with the administrator upon basic policies of administration of the act, and it shall meet not less than once a month.

This organization seems to be set up to provide a predominating influence of interests which are far removed from any knowledge of the aims and objects and requirements of scientific work.

In my opinion the board and committee should consist overwhelmingly of scientists and technologists, and the administrator himself should be one or the other. The committee, moreover, being advisory need not meet more than twice a year, at which times it can hear reports and go thoroughly into questions of policy and procedure. It then becomes a real advisory committee with reference to basic policies rather than a committee which would find itself dipping into details and grinding political axes.

Another political aspect of the bill is its substitution of control by the administrator for control by law. Many Americans are convinced that Congress has gone too far in vesting legal powers in the hands of bureaus under the President. This bill appears to go even further in that direction. Among the objectives of the bill are matters which should be controlled by law, for example: "the trend toward monopolized control of scientific and technical data and other resources," and not be put into the hands of an administrator with power.

There are many matters relating to patents, monopolies, and industrial practices which the office could place before Congress with recommendations for suitable laws to improve existing practices. This aspect would seem to be provided for in "Purpose of the Act, 9" which is "to provide guidance . . . . to the President, the Congress" whereas the act gives such sweeping powers to the administrator that instead of providing guidance he can resort to dictation.

I sincerely hope that your committee will give especial consideration to the wording of the act so that it shall not grant arbitrary powers to the administrator or to the Office, and again, I hope that the personnel will be changed so that the great majority will be scientists and technologists and that thereby the office shall be prevented from becoming a bone of contention between rival interests.

THE FOSTERING OF SCIENCE IN EDUCATIONAL INSTITUTIONS

I now come to that aspect of the bill which relates to the fostering of science in educational institutions. We have so many educational institutions now, including numerous lamentably weak ones, that it would seem generally undesirable to create new ones.

Because of the heavy taxation of wealth in coming years, it would seem desirable that financial aid be supplied to educational institutions which heretofore have depended on private support. Education should be available to all to pursue as far as individual ability justifies. But it is recognized that many youths are encouraged beyond their abilities, and this may be attributed to the sometimes desperate need of the colleges for funds which these students provide.

By improving the economic status of educational institutions a measurable increase in employment would be achieved, not only by increase in the number of institutional employes but also by the virtual employment of increased numbers of students

In many ways our educational institutions could be improved greatly to the advantage of science and the general welfare. However, the method of bringing this about implied in the wording of the bill is by no means satisfactory. There is too much danger of loss of freedom both by the institution and by the individual.

For science to flourish, freedom of thought and action are essential. Whatever may be said in favor of science under autocracy wherever regimentation enters, science suffers.

The first three paragraphs of the bill's declaration of policy give a very erroneous impression of the state of science in this country. Especially during the last forty years has it advanced phenomenally. The bill implies that vastly greater progress would be possible under the fostering care and authority of the Office of Science Mobilization presided over principally by nonscientists. The evidence in support of this view is certainly not impressive.

What might be done is to give added stimulation and support in the training of men for science and in the research conducted by institutions. But in giving this stimulation and support it would be far wiser if the Government agency would work in cooperation with the State governments, both lending financial support in accordance with general rules of procedure carefully drawn to avoid infringement of essential freedom necessary to the best accomplishment in scientific work. All this should be thought out carefully by men of broad vision and experience in scientific matters. The bill as drawn appears not to have come out of such a background. Such men as J. B. Conant, K. T. Compton, R. A. Millikan, and others that could be named are conspicuous by their absence from the hearings and correspondence and there is no evidence that they had any part in drawing up the bill.

SCIENTIFIC DEVELOPMENTS IN RELATION TO INDUSTRY

We now come to the third part—scientific developments in relation to industry. A very large part of the testimony is directed to this phase of the subject. Unfortunately it is, I should say, the least impressive part of the testimony, and gives the least genuine support to the bill. Judge Arnold's contribution is an obviously prejudiced attack on what he designates as cartels and in making the attack he casts great discredit on our industrial leaders as though they were the force of unrighteousness like a leech sapping the vitality of an otherwise righteous people. Judge Arnold may believe this to be true but against it there is strong evidence which your committee seems inclined to discount or avoid. The remedy for any evils due to cartels should rest with Congress, which, at the same time could pass laws freeing silver to the American people and putting a quietus on such restraining activities as those of James Caesar Petrillo.

Judge Arnold also attacks the practice in the use of patents. I am sure patent laws could be and should be improved, but the general subject of industrial development of new products and their exploitation seems too great for Judge Arnold to grasp. In general it may be said that new products are brought out as fast as practically possible. It costs money not to bring them out, but it also takes time to commercialize an invention. If brought out too soon there is loss due to servicing, replacement, and alterations; if too late there is development expense without a return. This is the condition which pertains especially to the small company.

Present practice in patent law does give an advantage to the large company, but this could be remedied. The main consideration of patents is to decide what is invention and what are its limitations and then to establish the limitations so all can understand what they are. This should be done by Congress and not by an administrator of the Office of Science Mobilization.

We must now consider some aspects of the conduct of scientific research by industry. In the testimony there is repeated reference to the advantages of the large company over the small company in ability to afford research. This alleged advantage is not strictly true. It is the large company which finally has discovered that research pays, that it pays even though the immediate objective is not apparent. It is the large company which can afford long time and costly experimentation, but this is in line with a costly product. It is in the nature of the case that a small company could not engage in the manufacture of large turbogenerators. The large company is essential in American industry. But the large company also makes a great variety of products to which research is applicable, whereas the small company has a more limited product and therefore can get along with much less research. Lack of research by small companies is not due to inability to afford it but is due rather to lack of conviction of the value of benefits to be gained. Many small companies are directed by self-taught business men, often men of real ability, whose attention is demanded by many diverse phases of the business. Research to them is often just an item of expense, a luxury which eventually might or might not bring a return. Research to them often means getting answers to questions of the moment; a project which must wait six months or a year for fruition, might be grasped, but one which extends over two or three years would be hard to comprehend as a practical investment.

As the smaller companies come to understand what research can do for them they will not be kept from going into it. They would understand more readily if they were not so primarily sales-minded. The fact that small companies increasingly are going in for research indicates a growing understanding of its desirability.

CONCLUSION

It thus appears that the functions of the Office of Science Mobilization as outlined in the bill have been extended to and beyond the danger point. The bill as drawn creates a supercontrol of scientific and technical facilities which amounts to autocratic control of all property, programs, projects, processes, procedures, patents, and so forth, used or intended to be used in research, development, and production of goods or services. Any act so comprehensive involves a threat to the existing order of American life. If it is desirable at all—of which there is certainly a reasonable doubt—it should be studied by the best and most experienced minds and subjected to intense scrutiny from every angle.

Mention has been made of Presidents Conant and Compton and Professor Millikan in connection with the bill's impact on educational institutions. Such men as F. B. Jewett, W. R. Whitney, and Charles F. Kettering should certainly be consulted with reference to industrial research. The testimony already taken is extremely unconvincing. Some of it comes from men who seem to have given the actual bill scant attention; some comes from professors who appear to be interested mostly in the possibility of securing financial assistance; some comes from persons who obviously are unqualified to express an intelligent opinion. These generally favor the bill.

You, Mr. Senator, in a letter to A. R. Ellis, president, American Council of Commercial Laboratories, state that Henry Kaiser, William M. Jeffers, Donald Nelson, and the late Edsel Ford have approved the bill. The testimony which you sent me contains no letter from any of these men except Mr. Ford, and his letter, as I read it, hardly could be regarded as an endorsement.

I, therefore, beg leave to conclude by expressing the hope that you and your committee will give weight to the objections I have pointed out and will seek further counsel from those men who really are qualified to voice opinions on so important a measure. I thank you for giving me the opportunity of again expressing my views.

WALTER L. UPSON (M '20)
(Director of research, Torrington Manufacturing Company, Torrington, Conn.)

Cultural Training of the Engineer

To the Editor:

Mr. Boyajian's paper, "Cultural Training of an Engineer" in the January 1944 issue (Transactions section, pages 6–8) of *Electrical Engineering* has stirred a number of reactions in me which I shall attempt to record. I, too, speak as a parent (one 12-year-old son), and also as adviser to students in the earlier terms of the engineering course of study at Columbia University. My own training in educational methods and in psychology is limited, and limitations of time prevent the preparation of a commentary supported by references, figures, and so forth. Therefore these are my unstudied reactions to the paper.

First, I would state that Mr. Boyajian does well to address himself to parents, for they, jointly with the grade and secondary

schools, provide the influences which, in my opinion, shape young people. His suggestions on habit formation and the various "cultural" matters which he enumerates (a–g) should be the concern of every parent and school teacher. For it is my belief that by the time a boy enters college at 17 years of age he is well nigh "set" in his lifetime patterns. Clearly there has been a long 16 years of influence operating in a boy during his most plastic years. I believe many educators, Mr. Boyajian included, depend too much upon forces brought into action during the college years. But the torrent already is rushing tumultuously seaward—college provides a number of alternate channels.

His advice to parents, therefore, might include the strong injunction that the boy have freedom to seek his proper channel during those early college terms. Over 80 per cent of the boys who come to Columbia University are emotionally "set" for one career or another (each the result of dozens of different influences). Provision must be made for them to adjust and to discover more of their capacities and inclinations. At Columbia University this results in some 50 per cent of those initially called engineers redirecting their efforts and plans toward law, business, medicine, and in fact toward every sphere of study.

From the above one would gather that I consider Mr. Boyajian's statement of cultural or educational training too narrow. That is the case. But it may be noted that I believe the prescription should be written for life and not for the college years alone. I am not sufficiently wise to write a prescription for life, though in a fashion I am helping to administer some sort of mixture to our young son.

I cannot resist, however, making specific comments on Mr. Boyajian's own prescription, though I offer no proposals of my own.

Improper Study Habits. Most of the college students who come to Columbia University have had an easy time in high school and have not had to study outside of classes. Contrarily educational progress in college must be made via self-directed study, the classroom serving less for drill and more for inspiration. As to the physical conditions of study (radio on, desk, references, and so forth), these characteristics are acquired long prior to the college period.

Habits of Speech, Grammar, Social Character. These are well formed on entrance to college. Interesting measurements of speech characteristics have been made at Columbia (and at many other colleges). These and grammar are very definitely formed out of the influences of family and precollege schooling. The force and proper use of language for written and oral conveyance of thought are, I believe, related to subjects for thought or speech, mechanical skill in writing, vocabulary, and the aggressive characteristic of the individual. These develop through the whole youth of the child and little can be added in the college years, compared with the earlier increments.

Johnson O'Connor, who developed the human measurements laboratory at Stevens Institute of Technology, believes vocabulary is a very important factor in life. He notes the correlation between vocabulary and the outstanding success of leaders who often have had little "formal" training. Mr. Boyajian's statement, ". . . the knowledge of English—vocabulary and grammar—of the average freshman is fully adequate for his needs" relates to the above, as follows. I believe O'Connor has found little change in vocabulary as a result of college training. Therefore one must be ready to admit that a student will be limited in his understanding, conceptions, and in his statements within his vocabulary. The situation is analogous to an engineer's use of mathematical symbolism. Mr. Boyajian, himself, must be intimately familiar with dependence upon the language and vocabulary of mathematics for the work in electric-circuit analysis.

In conclusion, I would state that leadership, success, or whatever end results, comes not from a few college terms of application in a particular way to a few particular subjects, but is rather the product of a long series of influences and experiences, which begin at birth, continue through college years, and through all the years that follow.

A. D. HINCKLEY (M '38)

(Assistant to the dean of faculty of engineering and instructor in electrical engineering, Columbia University, New York, N. Y.)

To the Editor:

Engineers have tried for years to compress the educational curricula leading to technical degrees into as small a space of time as possible. The catalogues of engineering schools always have been replete with advanced courses in such subjects as turbine design and armature-winding techniques, the ultimate usefulness of which to the student is open to serious question. Because the bill of fare is so filled with these courses, there is no time, we are told, to add culture. So we turn out engineers indifferently grounded in fundamentals; filled with specialized and highly technical knowledge in a specific field, in which the whole practice may change before they have worked two years; and utterly unequipped to live in the world of varied interests which surrounds them.

Now comes Mr. Boyajian's paper entitled, "Cultural Training of the Engineer," (AIEE *Transactions, volume 63, January 1944, pages 6–8*) in which he advocates for "cultural" training just three simple instructions: the development of ability to study efficiently, to deal with others successfully, and to express oneself well. That, for the engineer, is to be culture.

No one can argue with the need which he envisions for the student to acquire these three skills. Such requirements are so obvious as to need no elaboration. In fact the first and third elements should be well mastered by the end of a first year in college. The second is more difficult and is one in which many engineers are woefully deficient. One may question whether a course in "practical psychology" of the Dale Carnegie type will do the job. Usually, the ability to get along with one's fellows is developed more by doing it than by reading about it.

Webster's dictionary defines culture as the "act of developing by education, discipline, training, etc., . . . the enlightenment and refinement of taste acquired by intellectual and aesthetic training." The three suggestions for minimum "cultural" instruction made by Mr. Boyajian go a little way along the route of the first definition; but they wholly miss the second.

The compressed "cultural" curriculum which is advocated in the paper suggests a number of important questions:

1. Is this curriculum just intended for use during wartime?
2. If not, why is there so much emphasis on the lack of time in the program for culture?
3. Are engineers to be educated solely for the engineering job they intend to do, rather than as broad and complete citizens of their country and the world?
4. How will engineers with such limited educational advantages grow up to their responsibilities in the social system with personal and cultural backgrounds which enable them to take their places among the practitioners of other independent professions?

It is suggested that engineers would be better fitted for their jobs, for life and its enjoyment, and to become members of a really independent profession, if the following changes in the educational system could be instituted:

1. Concentrate the technical portion of the curriculum on mastery of fundamentals as distinct from specialized courses, the subject matter of which, in these fast-changing times, may be obsolete before the student graduates.
2. Allow time in the first years of the curriculum for really cultural subjects and encourage the embryo engineers to dip into literature, art, languages, philosophy, economics, or any of the other myriad subjects which make a complete individual.
3. Extend the time needed for an engineering degree from four years to six or seven, if need be, to accomplish this. Some engineering schools have already done this; other professions such as medicine and law have required it for a long time, with important beneficial results to their members.

EDWIN FLEISCHMANN (M '29)

(Engineer, Washington, D. C.)

Horsepower Meter for Aircraft

To the Editor:

Despite all the propaganda of our air-minded friends who seek to avoid the inhibitions and traditions which exist in other elements (sea and land), I note that J. C. Luttrell and W. A. Petrasek speak of "The Horsepower Meter for Aircraft," in their article in *Electrical Engineering*, November 1943, page 501.

Why not use the term "wattmeter"? Are they so hidebound by tradition in this infant industry that they still think of horses to drag their planes around? Or did aviation start with Pegasus in the time of the Greeks?

PAUL MacGAHAN (F '42)

(Development engineer, Westinghouse Electric and Manufacturing Company, Newark, N. J.)

TVA Releases Annual Report

In the letter from C. M. Jansky (F '32) which appeared in the April issue of *Electrical Engineering*, page 159, the statement, "For example the private utilities of Wisconsin paid 46 cents per kilowatt hour in taxes. . ." should read: "0.46 cents per kilowatt hour."

NEW BOOKS . . .

The following new books are among those recently received from the publishers. Books designated ESL are available at the Engineering Societies Library; these and thousands of other technical books may be borrowed from the library by mail by AIEE members. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the prefaces of the books. All inquiries relating to the purchase of any book reviewed in these columns should be addressed to the publisher of the book in question.

Table of the Bessel Functions $J_0(z)$ and $J_1(z)$ for Complex Arguments. Prepared by the Mathematical Tables Project, Work Projects Administration of the Federal Works Agency, conducted under the Sponsorship of the National Bureau of Standards. Published by Columbia University Press, New York 27, N. Y., 1943. 403 pages, illustrated, 11 by 8 inches, cloth, $5. (ESL.)

Bessel functions of orders zero and one are encountered in the general solution of boundary-value problems in the theory of potential, heat conduction, and wave motion, when the domain is bounded by a circular cylinder. In particular, they occur in the problem of the propagation of electromagnetic waves with a straight wire as a guide, the theory of the skin effect for poorly conducting wires, the problem of ostillatory motion of a sphere in a viscous medium, the vibration of a heavy chain in a resisting medium, and other boundary-value problems. These tables are calculated to ten decimal places and a bibliography is provided.

Lubrication of Industrial and Marine Machinery. By W. G. Forbes. John Wiley and Sons, New York, N. Y.; Chapman and Hall, London, England, 1943. 319 pages, illustrated, $8\frac{1}{2}$ by $5\frac{1}{2}$ inches, cloth, $3.50. (ESL.)

This manual discusses the everyday problems that arise in lubricating engines and machines of various types, and offers practical solutions. Starting with a description of the fundamentals of distillation, cracking, refining, and so forth, the author proceeds to discuss the effects of heat, pressure, and metals on lubricating oils and the methods of applying lubricants. Later chapters deal with the lubrication of steam engines, hydraulic turbines, pneumatic tools, internal-combustion engines, machine tools, steel and paper mills, and wire ropes. Heat-treating oils and greases are discussed.

Time Bases. By O. S. Puckle, with a foreword by E. B. Moullin. John Wiley and Sons, New York, N. Y.; Chapman and Hall, London, England, 1943. 204 pages, illustrated, $8\frac{1}{2}$ by $5\frac{1}{2}$ inches, cloth, $2.75. (ESL.)

This book, based on a paper presented before the Institution of Electrical Engineers in 1942, is intended to cover the more important electronic devices available for producing the time axis in television receivers, cathode-ray oscillographs, engine indicators, and similar apparatus involving precise timing or measurement of time intervals. It aims to provide an introduction to the principles, and to deal with the construction, testing, and uses of these devices. Appendixes discuss the cathode-ray tube and the effects of time constants and other valve and circuit parameters.

Latin America. Americana Corporation, New York, N. Y., and Chicago, Ill., 1943. 126 pages, illustrated, $8\frac{1}{2}$ by 11 inches, cloth binding $2.50, cardboard, $2.

Based on the latest edition of the Encyclopedia Americana, this reference book presents a fundamental background of place names, products, movements, political and cultural leaders, events, objets d'art, and dates for anyone wishing to become thoroughly familiar with Latin American life. The Latin American countries are treated as a unit in arranging the important information about their geography, industry, agriculture, art, literature, politics, music, history, and international political and economic relations. Separate summaries of basic conditions in each of the Central American republics are also given. The volume is amply illustrated.

Table of Circular and Hyperbolic Tangents and Cotangents for Radian Arguments. Prepared by the Mathematical Tables Project, Work Projects Administration of the Federal Works Agency, conducted under the Sponsorship of the National Bureau of Standards; published by Columbia University Press, New York, N. Y., 1943. 410 pages, tables, 11 by 8 inches, cloth, $5. (ESL.)

This volume, which is a companion volume to the "Tables of Circular and Hyperbolic Sines and Cosines," published in 1939, gives circular and hyperbolic tangents and cotangents for radian arguments from 0 to 2 at intervals of 0.0001 and from 0 to 10 at intervals of 0.1. The tables are given to eight significant figures. There is a good bibliography.

Principles and Applications of Electrochemistry. Volume 2. Applications. By W. A. Koehler, Second edition. John Wiley and Sons, New York, N. Y.; Chapman and Hall, London, England, 1944. 573 pages, illustrated, $8\frac{1}{2}$ by $5\frac{1}{2}$ inches, cloth, $5. (ESL.)

Intended both as a textbook for students and as a reference work for the man in electrochemical industry, this book covers primary and secondary cells, electroplating, electrometallurgy, electrolysis, electric furnaces, and various special applications. New topics added in this edition include continuous tin strip plating, magnesium from sea water, fluorescent lamps, induction heating, and several new types of furnaces and storage batteries.

Thermodynamics. By J. E. Emswiler. Revised by F. L. Schwartz. Fifth edition. McGraw-Hill Book Company, Inc., New York, N. Y., and London, Englanu, 1943. 335 pages, illustrated, $8\frac{1}{2}$ by 5 inches, cloth, $3. (ESL.)

The important practical topics covered are steam power, vapor refrigeration, and air-heat engines. The theoretical treatment of energy, the laws of thermodynamics, permanent gases, mixtures, and the flow of fluids are kept to basic considerations, with the whole forming an introduction to the more abstract phases of the subject. New material on absorption refrigeration, gas turbines, gas cycles, adiabatic saturation, and supersaturation has been added in this edition.

Design of Machine Members. By A. Vallance and V. L. Doughtie. Second edition. McGraw-Hill Book Company, Inc., New York, N. Y., and London, England, 1943. 559 pages, illustrated, $8\frac{1}{2}$ by $5\frac{1}{4}$ inches, cloth, $4. (ESL.)

This text has been prepared for the use of students who have had some training in kinematics, mechanics, and factory processes. Upon this foundation the author develops the theory involved in the design of the elements of operating machines and points out the variations from theory required by practical applications. Considerable space has been devoted to engineering materials, factors of safety, utilization factors, and the selection of design stresses. Illustrative review problems are provided for each chapter.

Time Study Engineering. By W. H. Schutt. McGraw-Hill Book Company, Inc., New York, N. Y., and London, England, 1943. 426 pages, illustrated, 9 by 6 inches, cloth, $5. (ESL.)

Every detailed phase of time study is covered on the basis of specific machine studies and in a simplified form understandable by those unfamiliar with shop production methods. Shop production methods, machinery, and tools are completely explained as well as the step-by-step study that should be made of particular operations. New simplified explanations of speeds and feeds and detailed analysis for determining "line tasks" and controlling man power are given.

Beloved Scientist. By D. O. Woodbury, with a foreword by O. D. Young. McGraw-Hill Book Company, Inc. (Whittlesey House Division), New York, N. Y., 1944, 358 pages, illustrated, $9\frac{1}{2}$ by 6 inches, cloth, $3.50. (ESL.)

In this biography the versatility of Elihu Thomson is demonstrated effectively. As a pure scientist and as a practical engineer, his talents were directed along many lines, although his most noteworthy achievements were in the field of electricity. As business man, teacher, or administrator, he was in the front rank. The author has developed a history of the electrical industry and built it around the figure of Elihu Thomson and his brilliant contemporaries.

Complex Variable and Operational Calculus with Technical Applications. By N. W. McLachlan. The Macmillan Company, New York, N. Y.; The University Press, Cambridge, England, 1942. 355 pages, illustrated, $8\frac{1}{2}$ by $5\frac{1}{2}$ inches, cloth, $4.75. (ESL.)

A modern treatment of the operational method is offered in this book, with illustrations of its application to problems in radio, television, heat transmission, electrical circuits, and other technological subjects. The operational procedure advocated is believed to offer advantages in speed and ease over other methods. The book is intended primarily for engineers who use mathematics in solving technical problems.

Elementary Statistical Methods. By H. M. Walker. Henry Holt and Company, New York, N. Y., 1943. 368 pages, illustrated, $9\frac{1}{2}$ by 6 inches, linen, $2.75. (ESL.)

This textbook is based on courses given

in Teachers College, Columbia University. The author has aimed at a clear simple exposition that will make the text practically self-teaching and has given particular attention to the development of underlying concepts and to interpretation. Emphasis is placed upon statistical techniques, with the treatment including the limitations and advantages of each, the assumptions underlying it, and the interpretations which can be made from it. Some chapters have bibliographies.

Applied Safety Engineering. By H. H. Berman and H. W. McCrone. McGraw-Hill Book Company, Inc., New York, N. Y., and London, England, 1943. 189 pages, illustrated, 8½ by 5½ inches, cloth, $2. (ESL.)

This textbook places emphasis on the practical use of safety engineering rather than on methods and the reasons for them. After presenting the fundamental requirements for a safety program, the book describes how investigations should be made; how to write safety rules, regulations, and messages; how to hold safety conferences; and how to make talks and inspections. Each topic is illustrated by cases and specimens.

Manual of Firemanship. Issued under the authority of the Home Office (Fire Service Department) and published by His Majesty's Stationery Office, London, England, 1943. 119 pages, illustrated, 8½ by 5½ inches, paper, 2s.6d. Obtainable from British Information Services, 30 Rockefeller Plaza, New York, N. Y., 75 cents. (ESL.)

This is the third part of a "survey of the science of firefighting" prepared for the men and women serving in the National Fire Service of Great Britain, as a guide to modern principles and to the equipment available. This part deals with water supplies of all kinds: hydrants, fire mains, emergency and mobile supplies, piping, and water relaying.

Quantum Chemistry. By H. Eyring, J. Walter, and G. E. Kimball. John Wiley and Sons, New York, N. Y.; Chapman and Hall, London, England, 1944. 394 pages, illustrated, 8½ by 5½ inches, cloth, $5. (ESL.)

This book contains a systematic presentation of quantum mechanics from the viewpoint of its usefulness in developing the concepts of chemistry and physics. It provides an introductory treatment of reaction rates, optical activity, molecular structure, spectroscopy, and group theory. It has been written at the level of the graduate student in chemistry, and assumes a knowledge of calculus on the part of the reader.

Technique of Radio Design. By E. E. Zepler. John Wiley and Sons, New York, N. Y.; Chapman and Hall, London, England, 1943. 312 pages, illustrated, 8½ by 5½ inches, cloth, $3.50. (ESL.)

This volume by an experienced radio designer deals with problems that are linked closely with the daily routine work of an engineer in the development and testing of radio-receiving apparatus of all types. Such questions as the transfer of energy from the aerial, detection and frequency changing, selectivity, receiver noise, screening, undesired feedback, and distortion are treated rather comprehensively with attention to intimate details.

Table of Reciprocals of the Integers From 100,000 Through 200,009. Prepared by the Mathematical Tables Project, Work Projects Administration of the Federal Works Agency, conducted under the sponsorship of the National Bureau of Standards. Published by Columbia University Press, New York 27, N. Y., 1943. 201 pages, tables, 11 by 8 inches, cloth, $4. (ESL.)

This table expands tenfold the scope of existing tables in this interval, in which interpolation between tabular entries is somewhat difficult because of the large differences between the successive intervals in the existing tables of Oakes and Cotsworth.

Analytical and Applied Mechanics. By G. R. Clements and L. T. Wilson. Second edition. McGraw-Hill Book Company, Inc., New York, N. Y., and London, England, 1943. 475 pages, illustrated, 8½ by 5¼ inches, cloth, $3.75. (ESL.)

The mathematical and physical theory necessary for a thorough first course in mechanics is presented for use as a college text. A great many problems are included to demonstrate both obvious applications and logical extensions of the theory. This edition has been revised on a basis of actual classroom experience with the earlier edition and contains many new problems.

Medical Radiographic Technic. Prepared by the technical service department, General Electric X-Ray Corporation under the editorial supervision of G. W. Files. Published by Charles C. Thomas, Springfield, Ill., and Baltimore, Md., 1943. 365 pages, illustrated, 10½ by 7 inches, fabrikoid, $6. (ESL.)

This manual of the fundamental principles and practical methods of medical radiography is designed for X-ray operators. The book is illustrated by a wealth of photographs and detailed instructions for taking all the radiographs in general use. The book should be very useful to any operator.

Statistical Adjustment of Data. By W. E. Deming. John Wiley and Sons, New York, N. Y.; Chapman and Hall, London, England, 1943. 261 pages, illustrated, 8½ by 5½ inches, cloth, $3.50. (ESL.)

This is a practical reference and textbook on the adjustment of data, with emphasis on scattered portions of the subject that are difficult to find elsewhere and that, in the author's opinion, are becoming increasingly important. Different kinds of problems of adjustment are unified and brought under one general principle and solution. Statistical procedures for curve fitting and other adjustments by least squares are discussed.

Car Builders' Cyclopedia of American Practice. 16th edition, 1943. Compiled and edited for the Association of American Railroads, mechanical division; edited by R. V. Wright, R. C. Augur, and others. Simmons-Boardman Publishing Corporation, New York, N. Y., 1943. 1324 pages, illustrated, 12 by 8½ inches, fabrikoid, $5. (ESL.)

The new edition of this well-known reference book follows the style of its predecessor, with some improvements in form and with better indexes. It again brings up to date the record of American car designs and car equipment.

Technology and Livelihood. By M. L. Fleddérus and M. van Kleeck. Russell Sage Foundation, New York, N. Y., 1944. 237 pages, illustrated, 9 by 6 inches, paper, $1.25. (ESL.)

Prepared for the Russell Sage Foundation, this report is a study of the effect of recent changes in the productive capacity of our basic industries upon opportunities for employment and upon living standards. Information accessible in government publications has been assembled and summarized so as to be understood by those without experience in production or training in technology.

Radio Receiver Design. Part I. By K. R. Sturley. John Wiley and Sons, New York, N. Y.; Chapman and Hall, London, England, 1943. 435 pages, illustrated, 8½ by 5½ inches, cloth, $4.50. (ESL.)

This book presents the fundamentals of receiver design by a detailed stage-by-stage examination of the receiver, starting from the aerial. The present volume, the first of two, ends at the detector stage. Each chapter has a bibliography.

PAMPHLETS....

The following recently issued pamphlets may be of interest to readers of "Electrical Engineering." All inquiries should be addressed to the issuers.

Selection of Supervisors. By Harold W. Dornsife. California Institute of Technology, Pasadena 4, Calif.

Will You Help? Engineers Council for Professional Development, 33 West 39th Street, New York 18, N. Y., 8 pages, no charge.

Power Centers. Westinghouse Electric and Manufacturing Company, Sharon, Pa., 25 pages.

Metermax Combustion Control for Boiler Furnaces. Leeds and Northrup Company, 4907 Stenton Avenue, Philadelphia, Pa., 36 pages.

Price List of American Standards. American Standards Association, 29 West 39th Street, New York 18, N. Y., 23 pages.

How Accountancy and Engineering Share in Effective Tool Control. 6 pages. **How Business Engineering Benefits Business.** 8 pages. **How Waste Reduction Boosts Production.** 12 pages. George S. May Business Foundation, 111 South Dearborn Street, Chicago 3, Ill.

Magnetron Oscillator for Instruction and Research in Microwave Techniques. By J. Tykocinski Tykociner and Louis R. Bloom. University of Illinois, Urbana, 30 pages, 40 cents.

TRANSACTIONS SECTION

Preprint of Corresponding Pages From the Current Annual AIEE Transactions Volume

Transmission and Relaying Problems on the Fort Peck Project

ERIK FLOOR
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THE recently completed Fort Peck power plant with its substation and transmission facilities has several features which are unique and of particular interest. This paper will point out application problems and their solution in connection with power transmission and relaying.

The initial installation of generation at Fort Peck consists of one 38,888-kva 13.8-kv 128.5-rpm three-phase 60-cycle water-wheel generator. Ultimately, two more generators are to be installed, one a duplicate of this first unit and one smaller unit. The substation is located on the west bank adjacent to the powerhouse and at present has one large transformer bank consisting of three 16,667-kva single-phase transformers stepping up to 161 kv from generator voltage. A 15,000-kva three-phase shunt reactor is installed on the 13.8-kv bus just ahead of the power transformers. All switching, except for transmission-line disconnects, is performed at generator voltage, and all power circuit breakers are of the compressed-air type.

The only high-voltage transmission associated with this initial installation is the one 161-kv line extending to the Rainbow substation bus of the Montana Power Company at Great Falls, Mont. The total length of the line is 288 miles; it is of H-frame construction, and the conductor employed is about half 477,000-circular-mil steel-reinforced aluminum cable and about half 300,000-circular-mil copper. The line was built originally to feed power to the dam site from Great Falls for use during construction.

At the Montana Power Company, terminal of the 161-kv line, a bank of three 20,000-kva single-phase three-winding autotransformers step down to 105 kv for connection onto the Rainbow bus at that voltage. At this location switching is performed at 105 kv. The power transformers at both ends of the line have the neutral solidly grounded on the high-voltage winding.

Figure 1 shows a simplified one-line diagram of the Fort Peck installation, transmission line, and receiver system. This sketch includes the system elements which will be discussed specifically in subsequent paragraphs, and most of the equipment shown has been described previously.

The unusual length of the transmission line involved introduces interesting application problems. This line length, coupled with hydrogeneration, immediately suggests a study of transient-stability limits for faults occurring on the Montana Power Company system at or near the Rainbow substation bus. Because of the very great shunt capacitance inherent to a single line section of nearly 300 miles, problems concerning open-circuit voltages and synchronizing are of importance. Also, because of line length, relaying presents a special set of conditions which standard high-speed impedance relays cannot meet. The salient factors affecting these problems and the measures considered in reaching the solutions will be examined.

General-System Studies

The a-c network calculator was employed in studying the general system shown in Figure 1. The relative simplicity would permit manual calculations with reasonable accuracy, but the use of the calculator permitted complete study, including numerous points too time-consuming by manual methods.

Four variations of the system finally adopted were studied, and these four connections are shown in their bare essentials in Figure 2. Note that the principal difference lies in transformers and shunt-reactor application. Henceforth, these four systems will be referred to as systems *a*, *b*, *c*, and *d*.

Of interest is the fact that all four of these systems operate satisfactorily in the steady-state condition, that is, from a standpoint of load and voltage regulation. The differences appearing in voltage levels at the two load busses in the different systems always can be compensated adequately by control of excitation at the two terminals. The resultant exchange of reactive is sometimes objectionable for other reasons, but in the steady-state case it is always operative. The principal reason for considering the unusual voltage ratios of systems *c* and *d* that result in a "sloping" voltage characteristic was to study the possible advantage of accepting excessive line drop in a very long line under load and adjusting normal transformer ratios a full-voltage class to meet it. The inherent decrease in line-charging kilovolt-amperes is a further advantage. Generally, the disadvantages accruing from reduced voltage level overweighed advantages in the cases studied. These relative merits will be discussed more specifically in following paragraphs.

Synchronizing

The charging kilovolt-amperes of the 288-mile transmission line, when operating at 161-kv, is approximately 43,000 kva. Since the generator rating at Fort Peck is 38,888 kva, it is impossible to charge the line at normal voltage in the connection of system *a*, unless part or all of the charging capacity is supplied from Rainbow. This presents an operating inflexibility, since it is impossible to synchronize at normal voltage at Rainbow.

By adding the 15,000-kva shunt reactor and obtaining system *b*, sufficient

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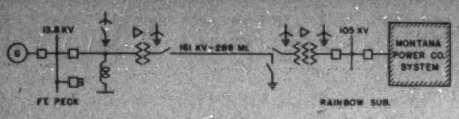


Figure 1. Simplified one-line diagram of Fort Peck system connection

line charging is canceled to permit the Fort Peck generator to "pick up" the line, and synchronizing can be accomplished at either terminal. Furthermore, when the line is energized from Rainbow, this shunt reactance cancels almost all of the voltage rise inherent to the line, so that only about three per cent differential exists across the synchronizing breaker (31 per cent for system *a*).

The sloping line-voltage characteristic of system *c* inherently reduces charging current to a figure of 38,000 kva but still does not permit synchronizing at Rainbow, since the generator charging capacity does not equal this figure, and because a voltage differential of 50 per cent exists across the synchronizing breaker at Rainbow. Such a voltage differential might be objectionable because of the large surge of reactive current that would occur immediately subsequent to closing the breaker. The sloping voltage characteristic presents ideal synchronizing conditions across the open switch at Fort Peck if the line is charged from Rainbow. The rising voltage characteristic very nearly follows the intentional "uphill slope," so that only seven per cent voltage differential from normal exists, a figure that could be met easily by generator regulation or be ignored altogether.

System *d* presents practically the same case as system *c* with respect to synchronizing, except that the line charging is further reduced by reduced voltage to a figure of 23,000 kva. The Fort Peck generator easily can supply this quantity, but the voltage differential across the open switch at Rainbow is then 66 per cent, an excessive figure.

System *b*, comprising full 161-kv voltage operation with a 15,000-kva shunt reactor, presents the most flexible case for system interconnection initiated at either terminal.

Stability

Since only a single-circuit line interconnects Fort Peck with the Montana Power Company, the tie is severed subsequent to each transmission-line fault, and there is no transient-stability limit. Transient stability becomes an important consideration, however, for faults and switching on the Montana Power Company system. Numerous high-voltage

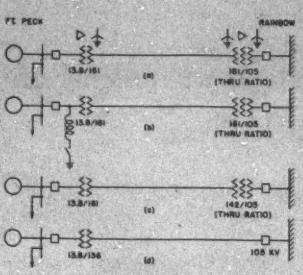


Figure 2. Variations of system studied

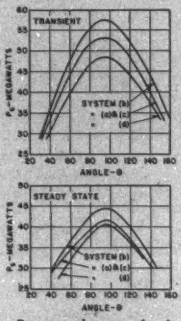


Figure 3. Power-angle curves for the systems studied

P_e = power output—Fort Peck generator
θ = angle between internal voltages

circuits emanate from the vicinity of the Rainbow bus, and, if Fort Peck were to swing out of step for faults or switching on these circuits, the effectiveness of the interconnection would be impaired seriously. For this reason stability was studied for faults on this adjoining system.

Power-angle curves applying to the different systems studied are shown in Figure 3. Note that system *b* offers a substantial increase in stability over the other systems studied, as demonstrated by the power-angle relations. All systems maintain stability for switching operations on the Montana system, and all systems are stable for single line-to-ground faults occurring near the Rainbow bus and cleared in relaying and breaker times actually obtaining on the Montana systems. System *d*, employing lower-voltage transmission, presents a marginal case for single line-to-ground faults, and this was one of the considerations that led to its discard. None of the systems studied are stable for multiphase faults near the Rainbow bus, although angle–time curves indicate that system *b* may provide a stable solution for many multiphase faults that occur some appreciable distance beyond the interconnecting point.

Of unusual interest is the fact that systems *a* and *c* show identical power-angle characteristics. This is a function of the large line-charging kilovolt-amperes in comparison with total generation that exists in this installation. If the voltage is lowered somewhat, line charging is reduced enough to permit the Fort Peck generator to operate at a lagging power factor and, of course, at a high internal voltage. This increase in internal voltage completely offsets the increased equivalent line impedance inherent to the lower-voltage operation.

The increase in stability with system *b* is due solely to the 15,000-kva shunt reactor which permits generator operation in the lagging range. The power-angle curves for the steady-state case (Figure 3) show that system *b* will be operating at 79 per cent of the steady-state limit when full-load kilowatts (35,000) are generated. It was believed that operation at above 85 per cent of this limit was likely to be unsafe during system disturbances, and this is borne out by the transient solution that indicates system *d* to present marginal stability for single line-to-ground faults beyond Rainbow. Systems *a* and *c* eliminate this uncertainty, but the considerable extra margin provided by system *b* for relatively small investment was believed good insurance.

Water Rheostat

The water rheostat was necessitated by the omission of the surge tanks because of wartime conditions. The origi-

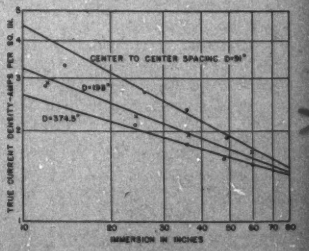


Figure 4. Results of field tests on water rheostats

Four-inch outside-diameter electrodes at 13.8 kv

nal plans provided for installation of three surge tanks of adequate size to provide satisfactory hydraulic stability and capacity for the ultimate installation of three units, with each surge tank connected to its individual penstock by a suitable riser. The surge rise and water-hammer pressure increases were computed on the basis of using a five-second governor time for full-opening and closing the turbine wicket gates. However, it was deemed inadvisable to use large quantities of critical steel plate for this project just after the entry of the United States into the war, and the contract, therefore, was canceled.

Actual War Installation

The completion of part of the power development was authorized subsequently, with the surge tanks omitted.

The omission of the surge tank for the installed unit developed the following conditions:

1. The governor time would have to be slowed down materially to avoid subjecting the tunnel, penstock, and turbine to excessive water-hammer pressures.

2. Involuntary rejection of line load due to line faults, or other reasons, would result in runaway of the unit unless measures were taken to avoid this.

Various schemes were investigated then with the view of securing smooth transition from steady line-load conditions to steady local-load.

The most promising of these schemes appeared to be the use of a water rheostat to replace temporarily the line load with an automatic arrangement for reducing the rheostat load by withdrawing the electrodes from the water, so that the unit could be transferred smoothly from the more or less heavy line load to the light local load. A detailed investigation of this procedure convinced the authors that such operation might result in hydraulic instability, taking the form of a series of governor swings of increasing intensity with unpredictable results.

We, therefore, suggested that, on the occurrence of a line fault and loss of line load, the unit be brought down automatically to the speed-no-load position and that the water rheostat be set at a fixed value and used only as a brake to avoid runaway speeds. A tank rheostat was installed in the powerhouse to provide for the suggested service.

The following provisions were planned to avoid runaway conditions as far as possible:

1. The line-breaker tripping relay was arranged to energize the rheostat-breaker closing mechanism and also to trip the governor speed-no-load solenoid, so that the governor would act to reduce the gate position to approximately speed-no-load position irrespective of speed changes. The rheostat load would be tripped off then by a suitable mechanism, the various adjustments being made in such a way that the unit would continue to run after the gate movement was completed but at speed approximately normal.

2. The electrical arrangement was such that the line breaker would open and the rheostat breaker would close on either of the following eventualities:

(*a*). Fault on the line.
(*b*). Opening of breaker at receiving end of line.

3. An electrical fault in the generator itself results in the field being opened and precludes the possibility of placing an electric load on the machine. In such case, the generator differential relays will act to trip the governor shutdown solenoid, causing the gates to close to the fully closed position. There is no method of avoiding a runaway speed under these conditions.

Water-Rheostat Tests

As stated previously, the water-rheostat tank in the powerhouse was designed for braking service only and was not suited, therefore, for carrying current continuously for testing purposes. To obtain information on the effect of variations in electrode spacing, size, and immersion, as well as for applying a steady load on the turbine during certain hydraulic tests, a temporary rheostat was rigged in the tailrace. The electrode size could be varied from $2^3/_8$ to 8 inches outside diameter, the immersion from zero to six feet, and the spacing from about 7 to about 30 feet. The voltage also could be varied from zero to 13.8 kv. The resistivity of the water was approximately 590 ohms per inch cube at 15 degrees centigrade and was found to vary with temperature according to the following formula:

$$\rho = \frac{820}{10^{0.0092t}}$$

where

ρ = resistivity in ohms per inch cube
t = temperature in degrees centigrade

The test results were reduced to terms of current density in amperes per square inch, as it was realized that limitation of current density was an important factor in successful operation. A few tests were made with twin electrodes, but it was soon apparent that the behavior of these was exceedingly complex, and the majority of tests was made with 4-inch and $8^1/_8$-inch outside-diameter electrodes

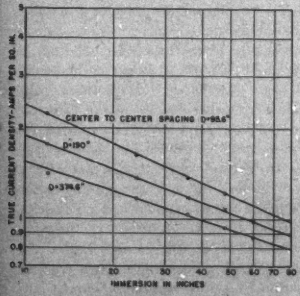


Figure 5. Results of field tests on water rheostats

$8^1/_8$-inch outside-diameter electrodes at 13.8 kv

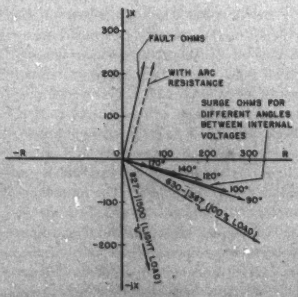


Figure 6. Impedance values as seen by relays at Fort Peck

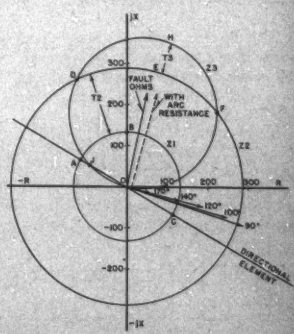


Figure 7. Distance-relay characteristics at Fort Peck

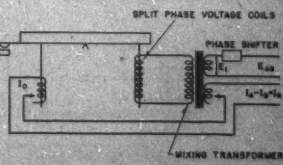


Figure 8. Schematic diagram of beam impedance element with modified characteristic

with one test of $2^3/_8$-inch electrodes. Results of tests on two electrode sizes are shown in Figures 4 and 5. The following deductions were made from the tests:

1. For immersions of 24 inches or more current density increased directly with voltage. For immersions of 12 inches or less current density increased as a power of voltage greater than unity.

2. For a given spacing (within the range tested) current density decreases as immersion increases.

3. For a given immersion (within the range tested) current density decreases as spacing increases.

Several tests were made by rejecting various line loads to various rheostat loads, and it was found that a suitable selection of rheostat loads could be made which would result in reasonable pressure changes in the penstock and reasonable speed changes of the machine, so that the test showed that the wooden tank in the powerhouse, when provided with the proper electrodes, will prove adequate for rejection at periodic intervals of loads of 15,000 kw and higher with the operating procedure as recommended. It was found impractical to build a water rheostat of large enough proportion that would be suitable for continuous operation or to be used for loads smaller than 15,000 kw.

Transmission-Line Relaying

With the construction of the Fort Peck line in 1934 it became evident, because of the small difference between load currents and fault currents, that proper protection could be provided only by zone-type distance relays, and, therefore, impedance-type relays were selected. Whereas there was little difference between the load-current and fault-current magnitudes, there was a wide difference in their phase-angle positions. Accordingly, the phase-angle characteristic of a standard impedance relay was accentuated and shifted to the proper operating zone by manipulation of the capacitor potential devices, and these relays have given very satisfactory service for several years. It is believed that this was the first instance of the application of a phase-angle discriminating feature to a distance relay in order to cope with the conditions on an extremely long transmission line. However, with the addition of the generating equipment at Fort Peck, the conditions with which the distance relay must cope have changed, and it has become desirable to extend further the phase-angle discriminating capacity of the impedance relays.

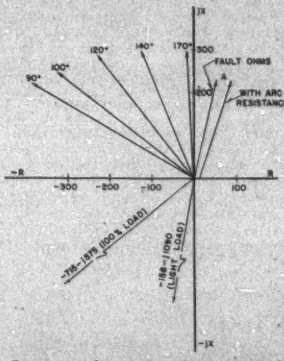
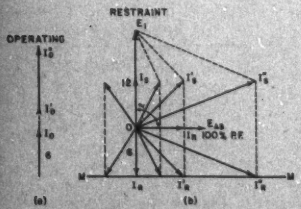


Figure 11. Impedance values as seen by relays at Rainbow

The new conditions presented to the relays are the presence of synchronizing surges on which relay action is not desired until the surges approach actual out-of-step conditions. The conditions, as an impedance relay located at Fort Peck sees them, are shown in Figure 6 which gives the magnitude and phase angle of the impedance ohms which are presented to the relays. The impedance vectors, designated by angles from 90 to 170 degrees, represent the ohm values as seen by an impedance relay obtaining its current and voltage from the 161-kv line at Fort Peck for different angles between the internal voltages at Fort Peck and Rainbow, as indicated. It may be noted that the maximum load-ohm vector is considerably longer than both the fault-ohm vector and the surge-ohm vectors, and, therefore, a standard impedance relay could be set to trip for faults but not for load currents. However, it has been determined that the system can experience surges up to 130 degrees between internal voltages and still recover synchronism after an external fault is cleared. If the internal voltages at Fort Peck and Rainbow deviate more than 130 degrees, actual out-of-step conditions are reached, and the line must be opened. It is clear from Figure 6 that a standard impedance relay, when set to trip for faults at Rainbow, will trip also for surge conditions from which the system can recover, since the surge-ohm values are too close to the fault-ohm values.

It was desired to have at Fort Peck a relay characteristic which would provide instantaneous tripping for faults over a portion of the line, time-delay tripping for faults over the remainder of the line, with time-delay backup tripping for faults beyond the Rainbow terminal, and instantaneous tripping on swings beyond a 130-degree angle between internal voltages. This tripping characteristic is depicted in Figure 7. Instantaneous tripping is provided by the impedance element $Z1$, and the directional element over the area bounded by the points A, B, 140 degrees, C, and 0. A second impedance element trips in the area bounded by the points O, J, D, E, and F. This second element trips through a timer, the operation of which is controlled by the directional element and a third element $Z3$. The $Z3$ element is a modified impedance element which operates for any impedance vector that terminates inside the circle O, J, D, H, F.

To change the characteristic of a beam-type impedance element into a displaced circular characteristic, as shown, no change in the beam element itself is required. Figure 8 shows schematically a beam element with the familiar split-phase voltage restraint on the rear end of the beam and a current coil on the front end. The restraint end of the beam, instead of being supplied with a voltage only, is supplied with the vector sum of a current and voltage. The delta current I_A–I_B is supplied to a primary winding of a transformer, while the voltage E_{AB} is supplied through a phase shifter to another winding. The secondary winding feeds the standard split-phase voltage coils. The current I_A–I_B also flows to a current coil on the contact end of the beam.



Figur 9. Vector diagram of current and voltage forces acting on the beam

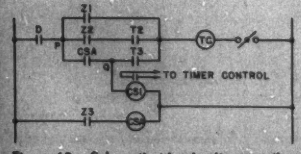


Figure 10. Schematic trip-circuit connection

The action which takes place to cause the element to have a circular characteristic can be seen from the vector diagram in Figure 9. This is drawn for the case where the center of the circle is to be placed on the X axis and passed through zero. The current I_R in the transformer winding is in phase with the voltage E_{AB} at 100 per cent power factor, but the voltage E, applied to the other winding is shifted 90 degrees leading. The operating energy on the front end of the beam is represented by the vector I, although this is the same current as that operating on the rear end of the beam. While the current on the front end is shown as a vector, no vector relationship exists between the pull on the front end and the pull on the back end of the beam, since the beam has substantially no response to the phase angle between the forces on the two ends. It is arranged that the current I_0 produces a mechanical force on the front end of the beam equal to the force produced by the current on the back end of the beam when no voltage is present. For fault currents lagging 90 degrees it is easy to establish the conditions for a balance point. For instance, if the voltage E_1 is assumed to be 12 units, then it is evident that the current I_R directly opposite must be 6 units in order for the net restraint of 6 units just to balance an operating force of 6 units. If the current lags the voltage less than 90 degrees (say I_R'), it must be increased to a value such that the vector sum of I_R' and E_1 (or I_3') still equals I_R', because the operating current I_3 has increased at the same rate, in order to maintain a balance point. It can be seen from an inspection of Figure 9 that the current I_R and I_0 for any angle must terminate on the straight line MM in order to make the scalar value of the vector sum $E_1+I_R=I_3=I_R=I_1$. In other words, the line MM represents the locus of balance currents for a given voltage E_1. Division of the voltage E_1 by the balance currents gives impedance values, which plotted on R and X co-ordinates gives a circle with its center on the X axis and passing through zero. The center of the circle can be placed on any other axis by regulating the angle α between E_1 and E_{AB}. For instance, if α is less than 90 degrees, the circle center is at a point between the $+X$ and $-R$ axes; if α is between 90 and 180 degrees, the center is between the $+X$ and $+R$ axes.

The aforementioned element follows the equation $EI\cos(\alpha+\theta)=E^2$, and such a characteristic has been used for a number of years in connection with an induction element. It may be noted, however, from the equation that, for close in faults where E approaches zero, the energy in the element also approaches zero resulting in sluggish indecisive action. It is interesting to note that a beam element following this same law is not operating under a low-energy condition. On the contrary, since heavier currents are obtained for close-in faults on long lines, the energy in the beam is even greater when the voltage is zero. Positive high-speed operation, therefore, at zero voltage is readily obtained by very slightly increasing the current pull on the front end of the beam with respect to the current pull on the rear end.

Rainbow Relays

The ohmic picture presented to the relays at Rainbow on the 105-kv bus is

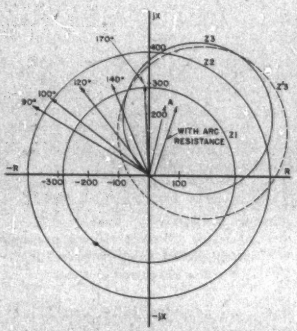


Figure 12. Distance-relay characteristics at Rainbow

shown in Figure 11. Here the only requirement is that the relay characteristic distinguish the surge ohms through 130 degrees and the load ohms from the fault ohms. Figure 12 shows the characteristic chosen. Here, however, it was desired to set $Z1$ element well into the transformer bank at Fort Peck with $Z2$ set beyond the low-voltage bus and $Z3$ even farther. Because of the long setting on $Z1$ element, and also to take care of possible future increases in the capacity at Rainbow, it was considered desirable to supervise the $Z1$ element through the $Z3$ element. This was done by moving the $Z1$ trip connection from point P to point Q on the schematic diagram in Figure 10. Placing the $Z1$ element effectively in series with the $Z3$ element means that the $Z1$ element can no longer trip independently for close-in faults, and the $Z3$ element must operate positively for all faults. As mentioned previously, the beam element possesses plenty of energy for faults giving zero voltage, even though its characteristic circle passes through zero. The element, however, possesses an additional advantage in that a definite margin of safety can be attained. This is done by passing the circle beyond zero as shown by the dotted circle $Z'3$ of Figure 12. This is accomplished very easily by increasing the current force on the front end of the beam in relation to the current force on the restraint end of the beam. The amount that the zero point is projected into the circle is regulated by the excess force on the front end of the beam as compared with the current force on the back end, and is accomplished very readily by manipulation of the current taps and core screw on the front end of the beam. The diameter of the circle, or the ohm setting, is regulated directly by manipulation of the current taps on the beam and on the transformer-primary current coil in unison, keeping the relative ampere turns constant.

With only a single high-voltage line involved, no high side switching is employed, and the differential relaying on the two terminal transformer banks cannot isolate low side faults. The impedance relays described will isolate

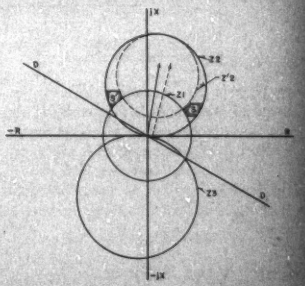


Figure 13. Distance-relay characteristics for carrier-current operation using four elements

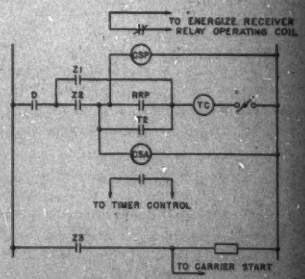
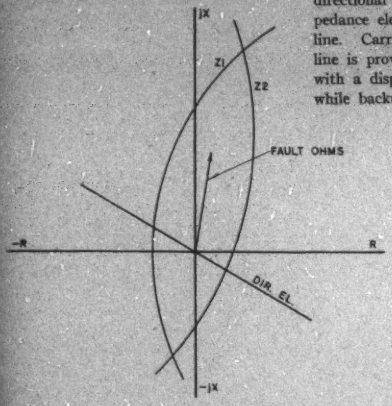


Figure 14. Schematic trip connections for relays in Figure 13

promptly in each case phase faults occurring at the far end of the line, but ground faults will not be handled if they occur on the low-voltage side of the transformers. For this reason the differential relays at each location are arranged to trip



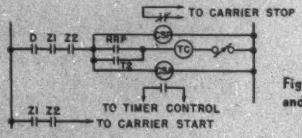


Figure 15. Distance-relay characteristics and connections for carrier-current operation using three elements

a three-phase grounding switch; an artificial phase fault is thus created; and the impedance relays clear promptly. These two grounding switches are shown in Figure 1. At Rainbow a high-voltage spring-closed switch is used, while at Fort Peck an existing 15-kv breaker is used.

Carrier-Relay Schemes

While carrier-relay operation was not involved on the Fort Peck project, it is interesting to see how the characteristics discussed previously could be fitted into a carrier scheme. There are several ways in which the standard three-zone impedance relay can be provided with various combinations of characteristics and be used in a carrier arrangement suitable for long lines. Figures 13 and 14 show one possible combination. Carrier is started for external faults by the $Z3$ element with a displaced circular characteristic. Instantaneous tripping independent of carrier is provided by the directional element D and the $Z1$ impedance element over a portion of the line. Carrier tripping over the whole line is provided by D and $Z2$ element with a displaced circular characteristic, while backup time tripping beyond the line is provided by D, $Z2$, and $T2$ elements.

In some cases it may happen that the maximum swing conditions from which the system may recover involve minimum ohmic values for which tripping is not desired in the general region S and S'. The $Z2$ element can be made unresponsive to these surge-ohm values without changing its response to fault ohms by contracting the circle into the position shown by the dotted circle $Z'2$. It may be recalled that the zero point on the R and X diagram definitely can be placed inside the circle by overbalancing the current force on the front end of the beam. Conversely, the zero point definitely can be excluded from the circle by underbalancing the front-end current force. The diameter and position of the circle are regulated as before by the current taps on the operating and restraint ends of the beam. It is, therefore, evident that the circles $Z1$ and $Z'2$ can be positioned, so that tripping on severe synchronizing surges is prevented, but adequate coverage of the fault-ohm area is obtained.

Since the characteristic circle of the beam element can be adjusted to any diameter and its center placed anywhere with respect to the R and X axes, another combination is suggested using even less elements. This is depicted in Figure 15 where the circles of $Z1$ and $Z2$ overlap to provide good coverage in the range of the fault ohms, restriction in the range of load current and surges, and also coverage for external faults. Carrier is started by $Z1$ and $Z2$ and is removed by D, $Z1$, and $Z2$ elements which also provide a time-delay backup. Complete carrier and backup protection, as far as the distance relay is concerned, is thus accomplished with only three elements per phase.

Conclusions

The further extension of the phase-angle discriminating feature of the impedance relays, which have provided protection for the Fort Peck line since 1934, has enabled this same type of relay to accommodate the more severe conditions imposed by the addition of generating capacity at Fort Peck.

The addition of the movable circular characteristic to a beam-type impedance relay, with the easy ability to regulate the diameter and position of the circle, has opened up new possibilities in the protection of electrically long lines without the necessity of increasing the number of relay elements.

The use of shunt reactors to equalize voltages and increase transient-stability limits will increase as long line sections at very high voltages become more prevalent.

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Steady-State Stability of Synchronous Machines as Affected by Voltage-Regulator Characteristics

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STEADY-STATE stability of synchronous machines is an old subject, and the fact that voltage regulators may on occasion increase the stability limit is more or less well known.[1] The present paper, however, aims to contribute to the knowledge of the subject by:

(*a*). Presenting a method for calculating directly the gain in steady-state stability with a given regulator and excitation system and also for predetermining the optimum regulator and excitation-system characteristics to give maximum gain in stability for a given synchronous machine or set.

(*b*). Presenting the results of calculations by the methods developed for certain typical systems so as to give some notion of the possible gains under various conditions.

The relations developed may be used to study the effects of regulator and machine characteristics, power factor, regulator location, and so forth. An important application of the analysis is the case of electric ship propulsion, where the size and weight of the generator and motor are in part determined by the steady-state stability characteristics. The method of analysis consists in first setting up the transient equations of the system, then considering small displacements from any given equilibrium condition. The equations for small displacements are linear and may be tested directly for stability.

Conclusions

From the results shown here, and from additional calculations which have been made, the following conclusions may be stated:

1. A properly designed voltage-regulating system can increase the steady-state stability limit of a synchronous machine by a considerable amount.

2. Fast regulator and exciter action and low transient reactance are desirable. On the other hand, the amplification factor of the regulating system must be co-ordinated properly with the machine and system constants rather than made as large as possible.

3. The possible gain in power limit for two synchronous machines is considerably greater than for a single machine connected to an infinite bus through a tie line.

4. Amortisseur windings have little effect on the possible gain in power limit.

5. Although the exact value of exciter time constant is not important, additional lags in the regulating system should be avoided, as they reduce the gain considerably. Some exciter time lag actually may be beneficial in increasing the permissible range of regulator amplification.

6. For maximum gain in power limit, a regulator with broad regulation and rapid response should be used. A very slow droop-correcting device could be used to maintain constant voltage over a range of load.

7. A regulator stabilizing transformer has little effect on the maximum gain but can permit a much narrower voltage regulation, which may be desirable for other reasons.

8. The division of transient reactance between two otherwise similar machines (acting as motor and generator) makes little difference, but, if the field time constants of two otherwise similar machines are different, the maximum power limit is obtained if the field of the machine with the smaller field time constant is regulated.

Analysis

Preliminary Remarks

Before entering on the detailed mathematical analysis a more or less general review of the fundamental concepts involved will be given.

For a single round-rotor synchronous machine connected to an infinite bus through a tie line or for two round-rotor machines the steady-state power transfer (with zero resistance) is given by

$$P = \frac{E_1 E_2}{x_1 + x_2} \sin \delta$$

where E is a machine excitation or the voltage of the infinite bus, x is a machine synchronous reactance or the tie-line reactance, and δ is the angle between the two excitation axes.

It may be recognized that in the steady state (or generally, if the effects of rotor circuits are neglected) there is analytically no distinction between a tie line with its infinite bus and a second machine. The distinction lies rather in the values to be assigned to the various parameters and in the interpretation of the quantitative results.

For two equal machines or for a machine connected to a tie line of equal reactance with $x_1 = x_2 = 1.0$ and with the excitations set at some fixed value, for example, to give rated current at unity power factor and unit terminal voltage

$$E_1 = E_2 = \frac{1}{\cos 45^\circ} = 1.414$$

(see Figure 6), and the power transfer is

$$P = \frac{(1.414)^2}{2} \sin \delta = \sin \delta$$

The power limit occurs at $\delta = 90$ degrees and is $P_{max} = 1.0$.

If, on the other hand, the excitations are not constant but are controlled so as to maintain unit voltage and power factor, then

$$E_1 = E_2 = \frac{1}{\cos \frac{\delta}{2}}$$

and the power transfer is

$$P = \frac{E_1 E_2}{x_1 + x_2} \sin \delta = \frac{\sin \delta}{2 \cos^2 \frac{\delta}{2}} = \tan \frac{\delta}{2}$$

Now the power transfer increases without limit as the angle δ is increased from 0 to 180 degrees. The new torque-angle curve crosses the old torque-angle curve at $\delta = 90$ degrees. The question of the meaning of this result, particularly of the possibility of stable operation in the region $\delta > 90$ degrees, now naturally arises; the answer is found in the kind of control used. If the excitations are controlled slowly, for example, by hand, so as to return the terminal voltage to unity only after a deviation is noticed, the power limit again will be found at $\delta = 90$ degrees. One may imagine the load increased in small steps. At each step the terminal voltage is returned to unity by an adjustment of the excitations, and then the system is tested for steady-state stability in the conventional way by noting whether or not a small increase in angle with fixed excitations results in an

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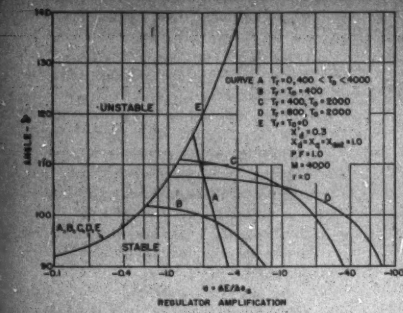
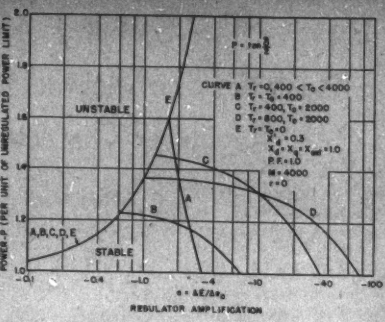

UNSTABLE
STABLE
A,B,C,D,E
CURVE A T_r=0, 400 < T_0 < 4000
B T_r = T_0 = 400
C T_r = 400, T_0 = 2000
D T_r = 800, T_0 = 2000
E T_r = T_0 = 0
X_d = 0.3
X_q = X_e = X_{tie} = 1.0
P.F = 1.0
M = 4000
r = 0
ANGLE - δ
e = ΔE/Δe_a
REGULATOR AMPLIFICATION

Figure 1 (left). Effect of automatic voltage regulator on steady-state stability limit

Figure 2 (right). Effect of automatic voltage regulator on steady-state stability limit


UNSTABLE
STABLE
A,B,C,D,E
CURVE A T_r=0, 400 < T_0 < 4000
B T_r = T_0 = 400
C T_r = 400, T_0 = 2000
D T_r = 800, T_0 = 2000
E T_r = T_0 = 0
X_d = 0.3
X_q = X_e = X_{tie} = 1.0
P.F = 1.0
M = 4000
r = 0
POWER - P (PER UNIT OF UNREGULATED POWER LIMIT)
e = ΔE/Δe_a
REGULATOR AMPLIFICATION

increase or decrease in power transfer. However, if the excitations are controlled automatically to maintain constant terminal voltage continuously and instantaneously, regardless of load or angle, and even during the stability test, the relation $P = \tan \delta/2$ will hold instantaneously, and there no longer is a stability limit. In order to maintain the constant terminal voltage required for such stable operation it is necessary to have a flat regulator (that is, one with an infinite amplification factor, $a = -\infty$) and no time lags in the regulator, exciter, or even in the main machine fields, so that the excitations are corrected instantaneously. Such action is, of course, practically unrealizable because of the time lags inherent in any system. Moreover, both excitations also increase without limit as the angle δ approaches 180 degrees.

It is shown in equation 33 that, for a single machine connected to an infinite bus through a tie line of reactance $x = 1.0$, instantaneous control of only one excitation is sufficient to allow stable operation at any angle up to 180 degrees as the amplification factor is increased, but the amplification factor now must be twice as large as that required if both excitations are controlled instantaneously. Of course, the conditions of unit terminal voltage and power factor imply that, in any case, the excitations or the infinite bus voltage must be adjusted (possibly by hand) to maintain these conditions. Thus, in the limit both excitations still approach infinity as before.

If the actual case considered is really a tie line to an infinite system, rather than two machines, motor and generator of equal size, it would seem more reasonable to study the condition in which the infinite bus voltage as well as the machine terminal voltage is maintained at unity, letting the terminal power factor fall where it may. Then with a tie-line reactance and machine reactance each equal to unity, the power limit unregulated can be shown to be $P_{max} = 0.866$, and "ideally" regulated (to maintain unit terminal voltage instantaneously) to be $P_{max} = 1.0$. The maximum possible improvement is seen to be very much smaller than for the two-machine case.

In order to make it easier to follow, the mathematical analysis is presented first as applied to a single machine and next, in less detail, as applied to two machines.

A. Single Machine and Tie Line. This section is concerned with the effect of a voltage regulator on the steady-state stability limit of a synchronous machine connected through an impedance tie to an infinite bus. The regulator is responsive to changes in terminal voltage or in voltage at any specified point on the tie line and acts on the field voltage of the synchronous machine. (The "regulator" of this section includes the whole regulating and excitation system.) The notation and assumptions of Park[3] are followed.

For the synchronous machine

$$\begin{aligned} e_d &= pG(p)E - z_d(p)i_d + [x_q(p)i_q](p\theta) \\ e_q &= G(p)E(p\theta) - x_d(p)i_d(p\theta) - z_q(p)i_q \end{aligned} \quad (1)$$

Similarly, for the tie line

$$\begin{aligned} e_d &= e \sin \delta + z(p)i_d - xi_q(p\theta) \\ e_q &= e \cos \delta + xi_d(p\theta) + z(p)i_q \end{aligned} \quad (2)$$

where

$z(p) = r + px$ for the tie line

δ is the angle by which the machine leads the infinite bus voltage e.

Machine-torque equation

$$T = \psi_d i_q - \psi_q i_d + Mp^2\theta \quad (3)$$

where

$M = 4\pi fH$

From equations 1, 2, and 3 the equations for small changes from a steady-state operating position are

$$\begin{aligned} \Delta e_d &= pG(p)\Delta E - z_d(p)\Delta i_d + x_q(p)\Delta i_q - \psi_{q0}p\Delta\delta \\ \Delta e_q &= G(p)\Delta E - x_d(p)\Delta i_d - z_q(p)\Delta i_q + \psi_{d0}p\Delta\delta \\ \Delta e_d &= z(p)\Delta i_d - x\Delta i_q + (e\cos\delta - xi_{q0}p)\Delta\delta \\ \Delta e_q &= x\Delta i_d + z(p)\Delta i_q - (e\sin\delta - xi_{d0}p)\Delta\delta \\ \Delta T &= i_{q0}G(p)\Delta E - [\psi_{q0} + i_{q0}x_d(p)]\Delta i_d + \\ &\quad [\psi_{d0} + i_{d0}x_q(p)]\Delta i_q + p^2M\Delta\delta \end{aligned} \quad (4)$$

The regulator introduces a change in field voltage E as a function of the change in *magnitude* of the terminal voltage e_a

$$\Delta E = g(p)\Delta e_a \quad (5)$$

where

$e_a^2 = e_d^2 + e_q^2$

and $g(p)$ is the operational expression for the action of the regulator

$$\begin{aligned} \Delta e_a &= e_d'\Delta e_d + e_q'\Delta e_q \\ e_d' &= e_{d0}/e_{a0} \qquad e_q' = e_{q0}/e_{a0} \end{aligned} \quad (6)$$

Then

$$\Delta E = g(p)(e_d'\Delta e_d + e_q'\Delta e_q) \quad (7)$$

If equation 7 is substituted in equations 4, equations 4 become

Δe_d	Δe_q	Δi_d	Δi_q	$\Delta\delta$	
$i_{q0}G(p)g(p)e_d'$	$i_{q0}G(p)g(p)e_q'$	$-\psi_{q0} - i_{q0}x_d(p)$	$\psi_{d0} + i_{d0}x_q(p)$	p^2M	$= \Delta T$
$pG(p)g(p)e_d' - 1$	$pG(p)g(p)e_q'$	$-z_d(p)$	$x_q(p)$	$-\psi_{q0}p$	$= 0$
$G(p)g(p)e_d'$	$G(p)g(p)e_q' - 1$	$-x_d(p)$	$-z_q(p)$	$\psi_{d0}p$	$= 0$
-1	0	$z(p)$	$-x$	$e\cos\delta - xi_{q0}p$	$= 0$
0	-1	x	$z(p)$	$-e\sin\delta + xi_{d0}p$	$= 0$

(8)

In order to test the stability of the system, the determinant of the coefficients of equations 8 is expressed as a polynomial in p, and the signs of the real parts of the p roots are investigated by Routh's or Hurwitz's criterion.

The required initial steady-state conditions for given E, e, and δ are

$$i_{do}=\frac{-(r_q+r)e\sin\delta-(x+x_q)(e\cos\delta-E)}{(r_d+r)^2+(x+x_d)(x+x_q)}$$

$$i_{qo}=\frac{+(x+x_d)e\sin\delta-(r_d+r)(e\cos\delta-E)}{(r_d+r)^2+(x+x_d)(x+x_q)}$$

$$\psi_{do}=E-x_d i_{do} \qquad e_{qo}=\psi_{do}-r_d i_{qo}$$
$$\psi_{qo}=-x_q i_{qo} \qquad e_{do}=-\psi_{qo}-r_q i_{do} \tag{9}$$

When amortisseur windings are neglected, the operational impedances are

$$x_d(p)=\frac{x_d' T_{do}p+x_d}{T_{do}p+1} \qquad x_q(p)=x_q$$

$$G(p)=\frac{1}{T_{do}p+1} \tag{10}$$

If it is assumed that the regulator and exciter performance can be expressed as a static change (a) in field voltage E per unit change in terminal voltage e_a, together with a time lag expressible as an equivalent single time constant T_r, then

$$g(p)=\frac{a}{T_r p+1} \tag{11}$$

Other more exact operational relations may be used in the equations, but equations 10 and 11 are the simplest and are sufficiently exact for an initial study.

If components of voltage caused by the rates of change of flux linkage and of angle are neglected, equations 8 become

Δe_d	Δe_q	Δi_d	Δi_q	$\Delta\delta$	
$i_{qo}G(p)g(p)e_d'$	$i_{qo}G(p)g(p)e_q'$	$-\psi_{qo}-i_{qo}x_d(p)$	$\psi_{do}+i_{do}x_q(p)$	p^2M	$=\Delta T$
-1	0	$-r_d$	$x_q(p)$	0	$=0$
$G(p)g(p)e_d'$	$G(p)g(p)e_q'-1$	$-x_d(p)$	$-r_d$	0	$=0$
-1	0	r	$-x$	$e\cos\delta$	$=0$
0	-1	x	r	$-e\sin\delta$	$=0$ (12)

If, in addition, armature and line resistance are neglected, equations 8 are reduced to

Δe_d	Δe_q	Δi_d	Δi_q	$\Delta\delta$	
$i_{qo}G(p)g(p)e_d'$	$i_{qo}G(p)g(p)e_q'$	$-\psi_{qo}-i_{qo}x_d(p)$	$\psi_{do}+i_{do}x_q(p)$	p^2M	$=\Delta T$
-1	0	0	$x_q(p)$	0	$=0$
$G(p)g(p)e_d'$	$G(p)g(p)e_q'-1$	$-x_d(p)$	0	0	$=0$
-1	0	0	$-x$	$e\cos\delta$	$=0$
0	-1	x	0	$-e\sin\delta$	$=0$ (13)

Equations 13 imply that the voltage equations are reduced to the form

$$\Delta e_d=-\Delta\psi_q \qquad \Delta e_q=\Delta\psi_d \tag{14}$$

From equations 13 the characteristic determinant is

$$D=i_{qo}G(p)g(p)e_d'x_q(p)xe\cos\delta-[\psi_{qo}+i_{qo}x_q(p)][x_d(p)+x]e\sin\delta+[\psi_{do}+i_{do}x_q(p)][x_q(p)+x-xG(p)g(p)e_q']e\times\cos\delta+p^2M[x_q(p)+x][x_d(p)+x-xG(p)g(p)e_q']-\psi_{qo}[-[x_q(p)+x]\times G(p)g(p)e_q'e\sin\delta+x_q(p)G(p)g(p)e_d'e\cos\delta] \tag{15}$$

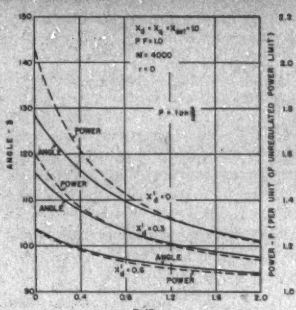


Figure 3. Effect of ratio of excitation and regulation-system time constant to field time constant on steady-state stability limit

Maximum stable operating conditions, by equation 34

For

$$x_d=x_q(p)=1.0,\ (\psi_{do}+i_{do}x_q(p))=E$$

B. Two Machines. The case of two synchronous machines with a voltage regulator responsive to the common bus-voltage magnitude and acting on either or both machine fields is considered in this section.

To simplify the analysis the armature resistances and the components of voltage caused by rate of change of flux and rate of change of machine angle were neglected finally in section *A*. These assumptions have been justified, not only from a common-sense consideration of the orders of magnitude of the quantities involved but also by the fact that test results have shown fairly good agreement with calculations. One then may write for each machine, as in equations 14

$$\Delta e_q=-\omega_0\Delta\psi_q$$
$$\Delta e_d=\omega_0\Delta\psi_d \tag{16}$$

For machine 1

$$\Delta e_{q1}=\omega_0 x_{q1}(p)\,\Delta i_{q1}$$
$$\Delta e_{q1}=-\omega_0 x_{d1}(p)\,\Delta i_{d1}+\omega_0 G_1(p)\,\Delta E_1 \tag{17}$$

For machine 2

$$\Delta e_{d2}=\omega_0 x_{q2}(p)\,\Delta i_{q2}$$
$$\Delta e_{q2}=-\omega_0 x_{d2}(p)\,\Delta i_{d2}+\omega_0 G_2(p)\,\Delta E_2 \tag{18}$$

Connection of the two machines to a common bus results in the relations

$$e_{d1}=e_{d1}\cos\delta_{12}-e_{q1}\sin\delta_{12}$$
$$e_{q1}=e_{d1}\sin\delta_{12}+e_{q1}\cos\delta_{12}$$
$$i_{d2}=-i_{d1}\cos\delta_{12}+i_{q1}\sin\delta_{12}$$
$$i_{q2}=-i_{d1}\sin\delta_{12}-i_{q1}\cos\delta_{12} \tag{19}$$

or, by differentiating

$$\Delta e_{d2}=\Delta e_{d1}\cos\delta_{12}-\Delta e_{q1}\sin\delta_{12}-(e_{d1}\sin\delta_{12}+e_{q1}\cos\delta_{12})\,\Delta\delta_{12}$$
$$\Delta e_{q2}=\Delta e_{d1}\sin\delta_{12}+\Delta e_{q1}\cos\delta_{12}+(e_{d1}\cos\delta_{12}-e_{q1}\sin\delta_{12})\,\Delta\delta_{12}$$
$$\Delta i_{d2}=-\Delta i_{d1}\cos\delta_{12}+\Delta i_{q1}\sin\delta_{12}+(i_{d1}\sin\delta_{12}+i_{q1}\cos\delta_{12})\,\Delta\delta_{12}$$
$$\Delta i_{q2}=-\Delta i_{d1}\sin\delta_{12}-\Delta i_{q1}\cos\delta_{12}-(i_{d1}\cos\delta_{12}-i_{q1}\sin\delta_{12})\Delta\delta_{12} \tag{20}$$

Substituting equations 20 in equations 18, one obtains

$$\Delta e_{d1}\cos\delta_{12}-\Delta e_{q1}\sin\delta_{12}=-\omega_0 x_{q2}(p)[(\Delta i_{d1}\sin\delta_{12}+\Delta i_{q1}\cos\delta_{12})+[e_{d1}\sin\delta_{12}+e_{q1}\cos\delta_{12}-\omega_0 x_{q2}(p)[(i_{d1}\cos\delta_{12}-i_{q1}\sin\delta_{12})]\Delta\delta_{12}$$

$$\Delta e_{d1}\sin\delta_{12}+\Delta e_{q1}\cos\delta_{12}=+\omega_0 x_{d2}(p)(\Delta i_{d1}\cos\delta_{12}-\Delta i_{q1}\sin\delta_{12})-[e_{d1}\cos\delta_{12}-e_{q1}\sin\delta_{12}+\omega_0 x_{d2}(p)[(i_{d1}\sin\delta_{12}+i_{q1}\cos\delta_{12})]\Delta\delta_{12}+\omega_0 G_2(p)\,\Delta E_2 \tag{21}$$

As in section *A*, the field voltages are given by

$$\Delta E_1=g_1(p)\,\Delta e_a=g_1(p)(e_{d1}'\Delta e_{d1}+e_{q1}'\Delta e_{q1})$$
$$\Delta E_2=g_2(p)\,\Delta e_a=g_2(p)(e_{d2}'\Delta e_{d2}+e_{q2}'\Delta e_{q2}) \tag{22}$$

where $g_1(p)$, $g_2(p)$ are the regulator and excitation-system characteristics for machines 1 and 2, respectively, and the torque equation of machine 1 is

$$i_{q1}G_1(p)g_1(p)(e_{d1}'\Delta e_{d1}+e_{q1}'\Delta e_{q1})-[\psi_{q1}+i_{q1}x_{d1}(p)]\Delta i_{d1}+[\psi_{d1}+i_{d1}x_{q1}(p)]\Delta i_{q1}+M_1p^2\Delta\delta_1=0 \tag{23}$$

Now from the voltage equations 19 and with the equations $e_d=-\omega_0\psi_q$ and $e_q=\omega_0\psi_d$ (by neglecting $p\psi$ and r_a), one may obtain

$$\psi_{q1}=\psi_{q1}\cos\delta_{12}+\psi_{d1}\sin\delta_{12}$$
$$\psi_{d1}=-\psi_{q1}\sin\delta_{12}+\psi_{d1}\cos\delta_{12} \tag{24}$$

Thus, the flux linkage is transformed just like the voltage, and it then may be shown that

$$i_{d1}\psi_{q1}-i_{q1}\psi_{d1}=-(i_{d2}\psi_{q2}-i_{q2}\psi_{d2}) \tag{25}$$

As the electrical torques of the two machines are equal and opposite, and if there are no mechanically applied damping

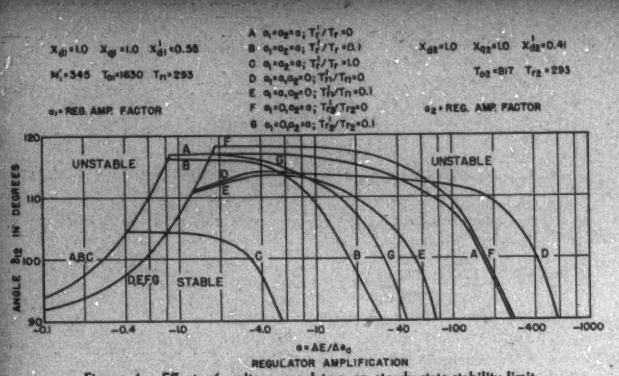


Figure 4. Effect of voltage regulators on steady-state stability limit

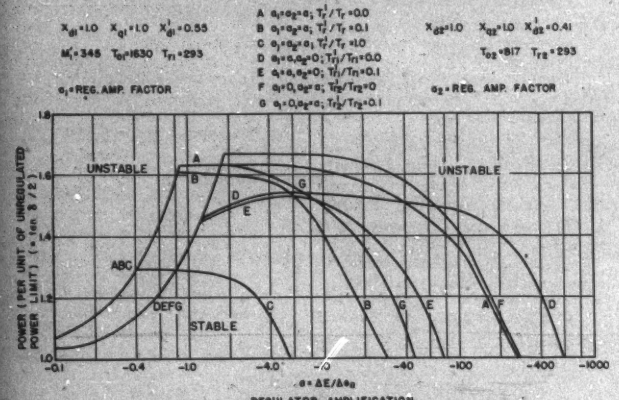


Figure 5. Effect of voltage regulators on steady-state stability limit

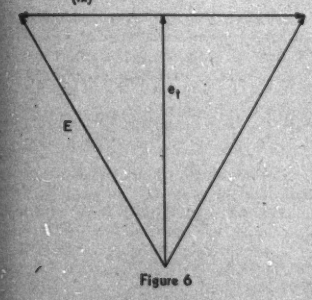


Figure 6

torques, the acceleration torques may be equated

$$M_1 p^2 \Delta\theta_1 = -M_2 p^2 \Delta\theta_2$$

$$= \frac{M_1 M_2}{M_1 + M_2} p^2(\Delta\theta_1 - \Delta\theta_2) = M' p^2 \Delta\delta_{12} \quad (26)$$

where

$$M' = \frac{M_1 M_2}{M_1 + M_2} = \text{equivalent system inertia}$$

Thus $M'p^2\Delta\delta_{12}$ may be substituted for $M_1p^2\Delta\theta_1$ in equation 23 to eliminate the extra variable $\Delta\theta_1$ and the extra torque equation. This simplification is still valid even if there are mechanical rotor damping torques, *if* $(D_1/M_1)=(D_2/M_2)$, in which case $(M_1p^2+D_1p)\Delta\theta_1=(M'p^2+D'p)\Delta\delta_{12}$ where $D'=D_1D_2/D_1+D_2$. If $(D_1/M_1)\neq(D_2/M_2)$, two torque equations are required. Considering the case of no mechanical damping, required five system equations are 23, 17, and 21, or

Δe_{d1}	Δe_{q1}	Δi_{d1}	Δi_{q1}	$\Delta\delta_{12}$	
$i_{q1}G_1(p)g_1(p)e_{d1}'$	$i_{q1}G_1(p)g_1(p)e_{q1}'$	$-\psi_{q1}-i_{q1}x_{d1}(p)$	$\psi_{d1}+i_{q1}x_{q1}(p)$	$M'p^2$	$=0$
-1	0	0	$\omega_0 e_{q1}(p)$	0	$=0$
$\omega_0 G_1(p)g_1(p)e_{d1}'$	$\omega_0 G_1(p)g_1(p)e_{q1}'-1$	$-\omega_0 x_{d1}(p)$	0	0	$=0$
$\cos\delta_{12}$	$-\sin\delta_{12}$	$\omega_0 x_{q2}(p)\sin\delta_{12}$	$\omega_0 x_{q2}(p)\cos\delta_{12}$	$-e_{q2}-\omega_0 x_{q2}(p)i_{d2}$	$=0$
$\sin\delta-\omega_0 G_2(p)g_2(p)e_{d1}'$	$\cos\delta-\omega_0 G_2(p)g_2(p)e_{q1}'$	$-\omega_0 x_{d2}(p)\cos\delta_{12}$	$\omega_0 x_{d2}(p)\sin\delta_{12}$	$e_{d2}-\omega_0 x_{d2}(p)i_{q2}$	$=0$

(27)

The determinant of the coefficients of equations 11 is

$$M'p^3\{x_{d1}x_{q1}+x_{d2}x_{q2}+(x_{d1}x_{q2}+x_{d2}x_{q1})\times\cos^3\delta+(x_{d1}x_{d2}+x_{q1}x_{q2})\sin^2\delta-G_1g_1\times[x_{q1}(x_{d2}-x_{q1})e_{d1}'\sin\delta\cos\delta+e_{q1}'(x_{d2}x_{q2}+x_{d2}x_{q1}\cos^2\delta+x_{q1}x_{q2}\sin^2\delta)]-G_2g_2[x_{q1}(x_{d1}+x_{q1})e_{d1}'\sin\delta+x_{d1}\times(x_{q1}+x_{q1})e_{q1}'\cos\delta]\}+(\psi_{d1}+i_{q1}x_{q1})\times\{(e_{d2}-x_{d2}i_{q2})[(G_1g_1e_{q1}'-1)x_{q1}-x_{d1}]\times\sin\delta-(e_{q2}+x_{q2}i_{d2})([(G_1g_1e_{q1}'-1)x_{d2}-x_{d1}]\times\cos\delta+x_{d1}G_2g_2e_{q1}')\}+(\psi_{q1}+i_{q1}x_{d1})\times(G_2g_2e_{d1}'x_{q1}(e_{q2}+x_{q2}i_{d2})+G_1g_1e_{d1}'x_{q1}\times\{(e_{d2}-x_{d2}i_{q2})(\psi_{q1}-i_{q1}x_{q1})\sin\delta-(e_{q2}+x_{q2}i_{d2})(\psi_{q1}-i_{q1}x_{d_1})\cos\delta\}+[\psi_{q1}(G_1g_1e_{q1}'-1)-i_{q1}x_{d1}][(e_{d2}-x_{d2}i_{q2})\times(x_{q1}+x_{q1})\cos\delta+(e_{q2}+x_{q2}i_{d2})\times(x_{q1}+x_{q2})\sin\delta] \quad (28)$$

where in equation 28 $G_1(p)$, $x_{d1}(p)$, and so forth have been written for convenience as G_1, x_{d1}, and so forth; ω_0 has been taken as 1.0; and δ_{12} has been written simply as δ.

For the special case $x_{d1}(o)=x_{q1}(o)=x_{q1}(p)=x_{q1}(p)=e_q=$ power factor $=1.0$ (two round-rotor machines with equal steady-state reactances and equal excitations) the determinant 28 reduces to

$$2\cos^3\frac{\delta}{2}M'p^3\Big\{[x_{d1}(p)+x_{d1}(p)]\times(1+\cos^2\delta)+[1+x_{d_1}(p)x_{d1}(p)]\sin^2\delta-[G_1(p)g_1(p)+G_2(p)g_2(p)]\sin\delta\sin\frac{\delta}{2}-2[G_1(p)g_1(p)x_{d1}(p)+G_2(p)g_2(p)x_{d1}\times(p)]\cos^2\frac{\delta}{2}\Big\}+[(2-\cos\delta)-(2+\cos\delta)\times x_{d1}(p)x_{d1}(p)]\sin^2\delta+[x_{d1}(p)+x_{d1}(p)](2+\sin^2\delta)\cos\delta-[G_1(p)g_1(p)+G_2(p)g_2(p)]\sin\delta\sin\frac{\delta}{2}-2[G_1(p)g_1(p)x_{q1}(p)+G_2(p)g_2(p)x_{d1}(p)]\cos^2\frac{\delta}{2} \quad (29)$$

Application

A. Single Machine and Tie Line

Equation 15 (or the similar equations derivable from equations 12 or 8) can be used to determine the stability limits of the single machine system over a range of circuit constants. The quantities which can be varied are:

1. Regulator amplification factor a.
2. Machine field time constant T_o.
3. Regulator and exciter time constant T_r (for the simple case of equation 11).

4. External reactance x.
5. Terminal power factor.
6. Transient reactance x_d'.
7. Moment of inertia M.
8. Location of regulator (that is, at machine terminals or along tie line).
9. Quadrature axis reactance x_q.
10. External resistance r.
11. Amortisseur characteristics.
12. More complex regulating systems, including stabilizers.

A study of the effects of the first three of these quantities has been made with the remaining quantities fixed at the values

$x=x_q=x_d=1.0$
Power factor $=1.0$
$x_d'=0.3$
$M=4{,}000$ (or $H=5.3$)
Simple regulator at machine terminals
$r=0$ (30)
No amortisseur

Under these conditions the maximum operating angle with no regulator is $\delta=90$ degrees, and with unit terminal voltage ($v_0=1.0$) the machine field and infinite bus voltages are $E=e=(\cos\delta/2)^{-1}$. Also, from equations 9

$$i_{do}=\frac{\sin^2\frac{\delta}{2}}{\cos\frac{\delta}{2}} \qquad \psi_{qo}=-i_{qo}=-\sin\frac{\delta}{2}$$

$$e_{do}'=e_{do}=-\psi_{qo}=\sin\frac{\delta}{2}$$

$$i_{qo}=\sin\frac{\delta}{2} \qquad e_{qo}'=e_{qo}=\psi_{do}=\cos\frac{\delta}{2} \qquad (31)$$

$$\psi_{do}=\cos\frac{\delta}{2}$$

From equations 10

$$x_d(p)=\frac{0{\cdot}3T_op+1}{T_op+1}$$

$$x_q(p)=1$$

$$G(p)=\frac{1}{T_op+1}$$

If some of these relations are substituted in equation 15, it becomes

$$+p^4 4M[+T_rT_o(1+x_d')]\cos^2\frac{\delta}{2}$$

$$+p^3 4M[T_o(1+x_d')+2T_r]\cos^2\frac{\delta}{2}$$

$$+p^2\left\{4M\left(2-a\cos\frac{\delta}{2}\right)\cos^2\frac{\delta}{2}+\right.$$
$$\left.2T_rT_o[(1+x_d')\cos\delta+(1-x_d')\sin^2\delta]\right\}$$

$$+p[2T_o[(1+x_d')\cos\delta+(1-x_d')\sin^2\delta]+$$
$$4T_r\cos\delta]$$

$$+\left(4\cos\delta-2a\cos\frac{\delta}{2}\right) \qquad (32)$$

Equation 32 is in a form such that, in addition to the quantities studied, the rotor-inertia M and transient-reactance x_d' can be varied also.

Results for Single Machine. Figures 1 and 2 show some of the results obtained. Figure 1 shows the maximum permissible operating angles between the machine and the bus, and Figure 2 shows the corresponding power limits as functions of the amplification factor a of the regulating system. Curve E, for no time lags in either the regulator or machine field, that is, for $T_r=T_e=0$, is seen from equation 32 to be given by the simple formula

$$a=\frac{2\cos\delta}{\cos\frac{\delta}{2}} \qquad (33)$$

The maximum stable operating angle is $\delta=180$ degrees (90 degrees between the machine direct axis and its terminals and 90 degrees between the machine terminals and the bus voltage) for $a=-\infty$, with a corresponding infinite power (see section, "Preliminary Remarks").

If $T_e\neq O$ (with $T_r=O$ still) the possible increase in power limit is at once very much reduced, and an upper limit of $(-a)$ is found (see curve A). It may be shown that, for all of the curves of Figures 1 and 2, the maximum stable operating angle occurs when the coefficients of p^1 and p^0 in equation 3 are simultaneously equal to zero. For these cases the maximum possible stable operating angle is given by the formula

$$\cos\delta=b-\sqrt{b^2+1} \qquad (34)$$

where

$$b=\frac{\left(1+x_d'+2\frac{T_r}{T_e}\right)}{2(1-x_d')}$$

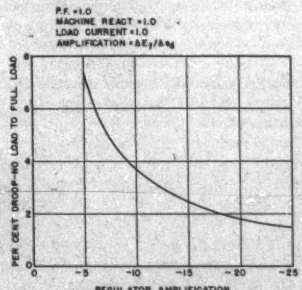


Figure 7. Relation between regulator amplification and voltage droop

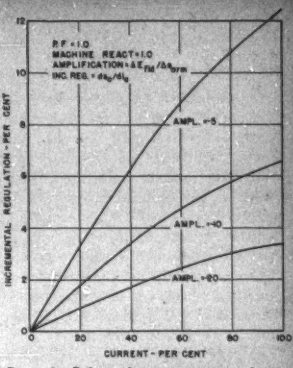


Figure 8. Relation between incremental regulation and regulator amplification

Figure 3 shows a plot of equation 34. This equation has been verified only in the range studied and should not be used over a much wider range without further check calculations by equation 32. The required values of regulator amplification factor a corresponding to the conditions of Figure 3 may be found from equation 33.

If $T_r/T_e=0$, the maximum possible stable operating angle is that corresponding to $T_e=\infty$. This may be seen by comparing equation 34 to the case $T_e=\infty$, $T_r=0$ in equation 32. Setting $T_e=\infty$ is equivalent to maintaining constant field flux linkages, in which case the steady-state power limit may be calculated by replacing the direct-axis synchronous reactance by the direct-axis transient reactance in the salient-pole synchronous-machine power-transfer formula, and the regulator action need not be considered. (Similarly, in the case of two regulated machines, the direct-axis reactances of both machines may be replaced in the limit by the direct-axis transient reactances.) Note that the power limits so obtained may be considerably different from those which would be found by replacing both x_d and x_q by x_d'.

Curves B, C, and D of Figures 1 and 2 show the further reduction caused by the introduction of a time lag in the regulation and excitation systems. Although a time lag decreases the maximum attainable angle and power limit, it allows operation over a considerably greater range in regulator amplification factor a.

If $T_e=0$ but $T_r>0$, no improvement in stability is possible. To the contrary, any attempt to control the field voltage reduces the stability limit. This is evident from equation 32. The detrimental

effect of a high ratio of T_r/T_e is also evident from Figure 3.

B. Results for Two Machines

1. Location of Regulated Excitation. It is not necessary that the field of each machine be controlled by the same amount. If there is any advantage in so doing, the relative amounts of field-excitation change produced on the two machines for a given voltage change may be made anything within reason. Therefore, calculations were made (by equation 29) to determine what the optimum arrangement should be. For this purpose the regulator and excitation-system characteristics were represented by

$$g(p) = \frac{a}{T_r p+1} = \frac{a}{293p+1} \tag{35}$$

This is the simplest possible characteristic; the exciter is assumed to have a 293-radian time constant, and all other lags in the regulating system are neglected.

Three arrangements were studied:

a. Regulation only on machine 1

$$g_1(p) = \frac{a}{293p+1} \quad g_2(p) = 0 \tag{36a}$$

b. Regulation equal on both machines

$$g_1(p) = g_2(p) = \frac{a}{293p+1} \tag{36b}$$

c. Regulation only on machine 2

$$g_1(p) = 0 \quad g_2(p) = \frac{a}{293p+1} \tag{36c}$$

Figures 4 and 5, curves *A*, *D*, and *F*, show the results and indicate that there is little difference among the three arrangements, so that the amount of stability gain is not critical to the relative field-excitation characteristics. The values of optimum amplification factor are smaller if the voltage regulation is equal on both machines, but this is only what should be expected, since the total required changes of field current on both machines tend to remain constant.

Comparison of Figures 4 and 5 with 1 and 2 shows also that the possible gain with two more or less similar machines is greater than for one machine and tie line. This appears to be a reasonable result when it is recalled that the lower the transient reactance the more the gain, and that the total transient reactance of two machines is, of course, smaller than that of one machine and a tie line.

2. Additional Lags in Regulating System. Since an actual regulating system may be made up of several stages, each having some time lag, the next step is to find out how important these lags are. The three regulator arrangements discussed in section 1 were, therefore, recalculated with the regulating system represented by the expression

$$g(p) = \frac{a}{(T_r p+1)(T_r' p+1)} = \frac{a}{(293p+1)(29.3p+1)} \tag{37}$$

This allows for a lag of $T_r' = 29.3$ radians in the regulator in addition to the lag of $T_r = 293$ radians in the exciter. The amount of possible gain in stability is seen by curves *B*, *E*, and *G* of Figures 4 and 5 to be somewhat smaller. Also, the permissible range of regulation or of amplification factor a is restricted still further. Although the reduction in gain is not alarming, it is sufficient to indicate that every effort should be made to reduce regulator lag.

Figures 4 and 5 also show curves *C* for the case of equal regulating effort on both machines with a 293-radian time lag T_r' in the regulator

$$g(p) = \frac{a}{(293p+1)^2} \tag{38}$$

The possible gain and allowable range of regulation are reduced greatly by this larger additional lag, as in the case of one machine.

Appendix. Relation Between Regulator and Excitation-System Amplification and Voltage Regulation

Figures 7 and 8 have been computed to show what the amplification factor (a) discussed in this paper means in terms of voltage regulation of the system. The vector diagram is as shown in Figure 6 for two equal round-rotor machines. From the diagram

$$e_t^2 + (ix)^2 = E^2 \tag{39}$$

For the regulated excitation system

$$E = E_0 - a(e_{t0} - e_t) \tag{40}$$

whence the equation for e_t is

$$(a^2-1)e_t^2 + 2a(E_0 - ae_{t0})e_t + (E_0 - ae_{t0})^2 - (ix)^2 = 0 \tag{41}$$

with

$$E_0 = e_{t0} = ix = 1.0$$

$$(a^2-1)e_t^2 + 2a(1-a)e_t + (1-a)^2 - 1 = 0 \tag{42}$$

Equation 42 allows one to calculate the voltage droop from no load ($i=0$) to full load ($ix=1$) for any amplification factor a. Results are shown in Figure 7.

Also, from equations 39 and 40 one obtains for the incremental regulation, defined as de_t/di, the relation

$$\frac{de_t}{di} = -\frac{x^2 i_0}{(e_{t0} - E_0 a)} \tag{43}$$

Results are shown in Figure 8.

The conclusions for this unity terminal power-factor case are that the over-all droop is about 40 per cent of the negative of the reciprocal of the amplification factor, and the incremental regulation increases from zero with increasing initial load, being equal to the over-all droop at about half load.

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A New Differential Analyzer

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Synopsis: This paper describes a new 14-integrator differential analyzer recently placed in service by the General Electric Company at Schenectady. This analyzer has a mechanical interconnection system but has integrators of novel design in that a Polaroid follow-up system is used rather than the more usual mechanical torque amplifiers.

TECHNICAL progress creates a need for tools which are capable of analyzing physical phenomena more accurately and rapidly. Electric calculating devices (d-c calculating boards, a-c network analyzers, and transient analyzers) represent significant attainments in fulfilling this growing need.

The development of the differential analyzer, both in this country and abroad, has kept a timely pace with technical progress. Early contributions to this development led to the construction of such an analyzer at the Massachusetts Institute of Technology.[3] Since that time several other similar analyzers have been constructed.[4,5,6,9,10,12,13] The value of such a device as a precision tool for the purpose of solving ordinary differential equations has been well established. Since 1935 General Electric Company engineers have used the University of Pennsylvania differential analyzer for the solution of many important problems. Most of the studies were made jointly with members of the Moore School staff, and some were of sufficient general interest to result in published articles.

With this experience and the increasingly important part played by the other various types of analyzers in carrying on analytical engineering work, the General Electric Company has built and recently put into operation at Schenectady a new differential analyzer. It is the purpose of this paper to describe this analyzer.

Fundamental Principles

The differential analyzer is fundamentally a device for the automatic solution of differential equations. One of the most important component parts of such a device is the means for accomplishing integration. While several known devices may serve as integrators, one which has served this purpose well over a number of years is the Kelvin wheel-and-disk type. This device is best described functionally by referring to Figure 1. In this figure the angular rotation of the turntable or disk, α, is proportional to the independent variable. The point of contact between the integrator wheel of radius R and this disk is restricted to a straight-line parallel to the axis of rotation of the wheel and passing through the center of the turntable. Its radial position from the center of this disk is defined as r. If there is no slip between the wheel and disk, then at any instant the arc $rd\alpha$ is equal to the arc $Rd\beta$, and, therefore

$$d\beta = \frac{r}{R} d\alpha$$

Consequently

$$\beta = \frac{1}{R} \int_{\alpha_1}^{\alpha_2} r d\alpha$$

and it follows that the angular rotation of the integrator wheel is the integral of the variable radius r with respect to the angular rotation α of the turntable between the limits, as defined by α_1 and α_2 with proper regard for signs and mechanical constants of the device. In such a device the radius r may be controlled by the rotation of a lead screw. Thus, integration can be accomplished in terms of the angular rotation of three shafts, namely, the turntable drive shaft, the lead-screw shaft, and the integrator-wheel shaft, the last always being the integral of the angular rotation of the lead-screw shaft with respect to the angular rotation of the turntable drive shaft.

Although these are the essential parts of an integrating device of this type, one additional element is most important in making it a practical device. In the solution of differential equations it is invariably necessary for the rotation of the integrator wheel to produce sufficient torque to drive the output shaft. The lightweight integrator wheel in contact with the turntable is not capable of producing this required torque. Some means of translating the angular position of the integrator wheel to another shaft through a means capable of supplying the required torque is necessary. The newly developed Polaroid follow-up system used to accomplish this purpose in the new General Electric differential analyzer will be described later in this paper.

The basic elements of a complete differential analyzer are shown in Figure 2. In this figure an input table, an output table, and an integrator are shown connected together with a motor which provides angular rotation proportional to the independent variable. As this motor rotates the integrator turntable rotates, and, simultaneously, the input- and output-table horizontal lead screws rotate, causing the carriage supporting the vertical lead-screw assemblies to move toward the right on both input and output tables. If, as this motion takes place, the crank on the splined shaft of the input table is rotated so as to keep a pointer on the curve drawn, and if this cranked angular rotation is made to drive the lead screw of the integrator, then the angular-rotation β of the integrator wheel is the integral of the function being followed on the input table with respect to the angular-rotation α of the motor drive, which is the independent variable. The angular-rotation β of the integrator wheel is transmitted through a follow-up system to the vertical lead-screw drive of the output table. Thus, the pencil supported by the output-

Table I. Integrator-Wheel Slip Measurements

Integrator Lead-Screw Setting	Integrator-Wheel Rpm	Equivalent Revolutions		Per Cent Difference	Output Torque (Pound-Inches)
		Integrator Wheel	Turntable		
−64.00	1,000	1,006.00	1,006.30	+0.030	0
−64.00	480	1,000.52	1,000.99	+0.047	0
−64.00	240	993.15	993.50	+0.035	0
−48.00	480	1,003.20	1,003.35	+0.015	0
−32.00	480	1,009.72	1,009.80	+0.017	0
−16.00	480	1,004.81	1,005.07	+0.026	0
+64.00	480	994.81	994.93	+0.008	0
+48.00	480	992.53	992.45	−0.008	0
+32.00	480	1,000.21	1,000.33	+0.012	0
+16.00	480	1,001.04	1,000.35	−0.069	0
+64.00	1,000	968.56	968.49	−0.007	5.0
+64.00	1,000	996.26	996.19	−0.007	8.0
+64.00	1,000	996.04	995.99	−0.005	9.0

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table carriage traces a curve which is the integral of the curve $r = K\alpha$ on the input table, with respect to the independent variable α, appropriate regard being given to constants and boundary conditions.

It is not always necessary to crank in functions, for, in many cases, they can be generated. In the example shown, for instance, the function $r = K\alpha$ being integrated is proportional to the independent variable α and, consequently, could be obtained directly from the motor drive with suitable gear ratios. However, this example was used as an elementary illustration of the function of the fundamental component parts of a differential analyzer. In general, input tables are used to crank in experimental functions which cannot be expressed conveniently analytically, but which, nevertheless, are known.

Design Considerations

Experience with the differential analyzer of the Moore School at the University of Pennsylvania in Philadelphia served as a basis for establishing certain criteria of performance which were desired in such a device to best meet the particular needs. Among the desired objectives were:

1. Flexibility.
2. Speed of solution.
3. Accuracy.
4. Low maintenance.
5. Reasonable time and cost required for construction.

While successful and satisfactory means for solving differential equations need not be patterned after existing analyzers, and it is realized that other means may offer excellent possibilities, these possibilities could be realized only after an extended development program. On the other hand, the use of an analyzer as a tool for the solution of design and system problems was desired at the earliest possible date. This fact played an important part in the formulation of the plans for building such a device.

Experience with the mechanical interconnection system at the University of Pennsylvania, which is similar to that employed in the analyzer described by Vannevar Bush, indicated that this system has a high degree of flexibility that is very desirable in a device to be used for the solution of many different types of problems. Such a system has proved satisfactory over a number of years of relatively continuous operation in several analyzers. With the wholehearted cooperation of the University of Pennsylvania, drawings, patterns, and so forth, already completed for this part of the analyzer were made available. Professor

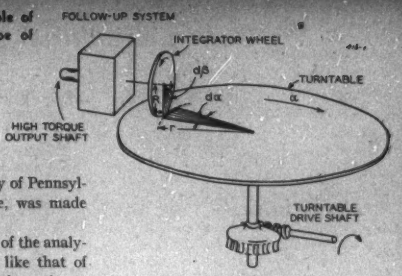

Figure 1. Fundamental principle of the Kelvin wheel-and-disk type of mechanical integrator

Irven Travis of the University of Pennsylvania, now in active service, was made available as consultant.

While the mechanical part of the analyzer was constructed mainly like that of the University of Pennsylvania analyzer, the mechanical torque amplifiers were replaced by General Electric Polaroid follow-up systems of novel design. The use of these new devices made it possible to make desirable and significant changes in the design of the integrator itself. Tests on these new integrators have shown that they contribute toward improved

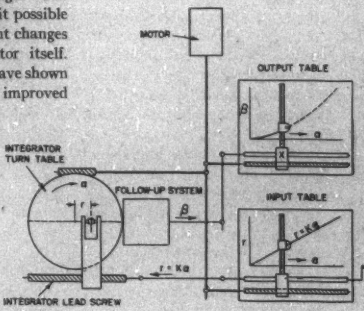

Figure 2. Schematic representation of the interconnections of the basic differential-analyzer elements

analyzer performance. This improved performance is realized in attaining a shorter solution time without sacrificing the desired degree of accuracy. Also, since adjustments once made need not be made periodically, as is the case with the conventional mechanical analyzer, time lost through maintenance is kept at a minimum.

The Polaroid Follow-up System

Mechanical torque amplifiers, as used on existing analyzers, require that, in order to change the position of the output shaft and produce driving torque, a finite torque be applied to the integrator wheel. Thus, there is a finite ratio between output and input torques, and the device is correctly named a torque amplifier. In contrast with this, the new Polaroid follow-up system is not a torque amplifier.

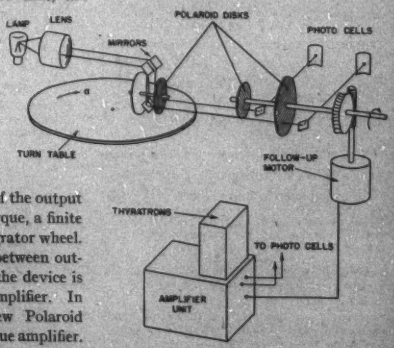

Figure 3. Schematic representation of the Polaroid follow-up system

The position of the output shaft is controlled by the position of the integrator wheel by means of polarized light beams which form the only link between the integrator wheel and the output shaft. Consequently, there can be no direct feedback, and the concept of a relation between input and output torques has no significance.

The operation of this Polaroid follow-up

system[11-14] can be explained best by referring to Figure 3. On the shaft of the integrator wheel, which is in contact with the turntable, is rigidly mounted a Polaroid disk. This shaft turns on jeweled bearings as the turntable is rotated. Light from a lamp source is brought through a condensing lens and infrared eliminating filter system. The infrared filter is necessary in order to eliminate that portion of the spectrum which is least polarized by the Polaroid system. Light from the condensing lens is directed to a set of mirrors supported rigidly on the integrator-wheel carriage. These mirrors reflect the incoming horizontal light vertically downward as two separate parallel beams. These beams in turn are intercepted by a second set of mirrors directly below, which reflect the incoming light as two horizontal beams which pass through the Polaroid disk. This Polaroid disk polarizes the two beams of light in the direction of the axis of polarization indicated by the parallel lines shown. These two parallel beams of polarized light continue and pass through separate Polaroid disks on the output shaft. One of these Polaroid disks is made larger than the other, and the axes of the integrator wheel and output shaft are displaced in parallel relation in order to make this separation of light beams possible. The two output-shaft Polaroid disks have their axes of polarization displaced by 90 degrees with respect to each other. Each beam, as it comes through its respective Polaroid disk, is again reflected horizontally at right angles to the incident beam. Each of these two beams falls upon a photocell.

If the axis of polarization of the Polaroid disk on the integrator-wheel shaft lies intermediate between the two axes of polarization of the Polaroids on the output shaft, then the light intensity is the same on both photocells. If the integrator wheel becomes slightly displaced from this intermediate position of balanced light, then one photocell receives more and the other less light. The direction of this displacement determines which of the two photocells receives more light, and, consequently, which receives less.

The two photocells form two branches of a bridge circuit which is balanced when the axis of the Polaroid disk on the integrator wheel shaft is intermediate between the axes of polarization of the two Polaroid disks on the output shaft. Any unbalance between the two light beams falling on the photocells causes a corresponding directional unbalance in this bridge circuit, which in turn is amplified, so as to control the firing of thyratron tubes. The controlled current through these tubes flows through a split-field series follow-up motor, causing it to turn in the direction required to maintain the balance of the photocell bridge circuit.

The basic circuit required to translate the photocell signal to the motor driving the output shaft is shown schematically in Figure 4. It is seen that the photocells are connected in series, and the midpoint is connected to the grid of one of the amplifier tubes. The grid of the second amplifier tube is adjusted and maintained at a potential so as to equalize the plate

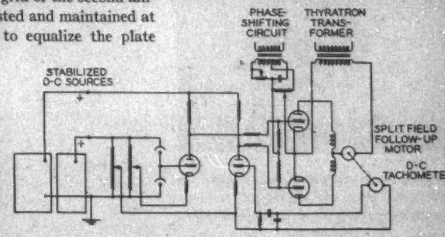

Figure 4. Schematic circuit diagram of the photocell amplifier and thyratron follow-up motor drive

voltages on the two amplifier tubes when the two photocells receive an equal amount of light corresponding to balance. Thus, under balanced light conditions, the voltage from plate to plate of the amplifier tubes is zero. A displacement of the integrator wheel in one direction, with the output shaft stationary, causes a d-c voltage to appear between these two plates. If the direction of displacement is reversed, the polarity of this d-c voltage is reversed. The desired directional signal is thus available between the plates of the two amplifier tubes. This signal in turn is brought to the grids of the two thyratron tubes, making one grid positive with respect to the other for a displacement of the integrator wheel in one direction, and one grid negative with respect to the other one for a displacement in the opposite direction. Thus, with one thyratron in each half of the split-field winding, and with alternating current applied to the thyratrons, field and armature in series as shown in Figure 4, a displacement of the integrator wheel with respect to the output shaft causes one or the other thyratron to conduct, the one conducting depending on the direction of this displacement.

It is desirable under balanced conditions that these two thyratrons conduct a small current equal in the two tubes for high sensitivity, thus producing no average motor torque. Also, the motor torque should increase rapidly and smoothly with angular displacement of the integrator wheel from the position of balance. In order to accomplish this, an a-c voltage adjustable in amplitude and phase with respect to the alternating current applied to the motor is introduced, as shown in Figure 4. When this a-c grid voltage

Table II. Typical Sine-Wave Growth Measurements

Maximum Integrator-Wheel Speed	Amplitude (Revolutions of Lead Screw)	Average Growth Per Cycle (Revolutions)	Per Cent Growth Per Cycle	Step Down	Gears for Train
970	50.00	0.525	1.05	None	None
780	40.00	0.400	1.00	None	None
390	20.00	0.194	0.97	None	None
510	60.00	0.225	0.375	None	None
335	40.00	0.175	0.437	None	None
170	20.00	0.135	0.675	None	None
262	60.00	0.135	0.225	None	None
175	40.00	0.128	0.320	None	None
87	20.00	0.104	0.520	None	None
200	64.00	0.129	0.202	1:4	1 pair
200	32.00	0.130	0.406	1:4	1 pair
200	16.00	0.123	0.770	1:4	1 pair
600	64.00	0.158	0.247	1:4	1 pair
1,000	64.00	0.174	0.272	1:4	1 pair
600	32.00	0.147	0.459	1:4	1 pair
1,000	32.00	0.162	0.506	1:4	1 pair
200	64.00	0.090	0.141	1:16	2 pairs
200	32.00	0.091	0.284	1:16	2 pairs
200	16.00	0.084	0.525	1:16	2 pairs
600	64.00	0.103	0.161	1:16	2 pairs
1,000	64.00	0.100	0.156	1:16	2 pairs
600	32.00	0.091	0.284	1:16	2 pairs
1,000	32.00	0.096	0.300	1:16	2 pairs

Figure 5. Integrator output-shaft motor drive showing the worm and compound gear and the optical arrangement of the Polaroid disks and mirrors

In back of the motor drive is shown the magnetic-clutch arrangement in the integrator lead-screw shaft

Figure 6. Top view of integrator unit showing the details of the carriage assembly and of the carriage drive

Figure 7. Top view of one of the double integrator-unit assemblies

The steel cabinet underneath the integrator table contains the thyratron transformer, auxiliary transformers, time-delay relay for the thyratron plate circuits, and various switches

lags the a-c motor voltage by approximately 90 degrees, the d-c voltage from the amplifier causes firing of the thyratrons over increasing portions of the positive half of the a-c motor voltage wave, the portion being continuously increased over the entire positive half cycle depending upon the magnitude of the d-c signal from the amplifier. Thus, the sensitivity is determined mainly by the d-c volts output per degree of angular displacement of the integrator wheel with respect to the balance point corresponding to equal illumination on the two photocells.

It is well known that, in sensitive follow-up systems such as this, stability is one of the most difficult problems. In particular, where the conditions of operation, as to speed, load, acceleration, inertia, and reversing, range over the extremes which are necessarily encountered in operating a flexible device such as this one, it attains most difficult proportions. Some effective means of stabilization is essential to satisfactory performance. One means of attaining stability is illustrated in Figure 4. The d-c tachometer shown is mounted on the same shaft as the d-c motor armature. It furnishes an output voltage proportional to speed which is used as an indication of output-shaft speed, and also through a resistance-capacitance network gives a signal across a resistance which has a component proportional to rate of change of speed. This signal is applied to the grid of the second amplifier tube as shown. In the case of a quick displacement of the integrator wheel requiring high acceleration of the motor, this signal partially counteracts the signal due to the photocell light unbalance, thus causing the output shaft to approach the position of balance more gradually than would be possible otherwise. Hence, with proper adjustment, the tendency to overshoot is diminished, and sustained oscillations or "hunting" cannot exist. This system of stabilization has been used with good results.

When several integrators are cascaded, the general stability problem becomes more difficult. Substantial progress toward the goal of further improved stability under these conditions has been made.

Figure 5 illustrates the output-shaft motor drive with cover removed. This shows the two output-shaft Polaroid disks and mirrors which reflect the two polarized light beams on the photocells. It also shows the follow-up motor mounting and the worm-gear drive. The worm gear is made of a special compound to withstand mechanical wear. Figure 6 is a top view of the integrator showing the carriage supporting the integrator wheel, Polaroid disk, mirror assembly, and the glass turntable.

The Integrators

The integrators fundamentally are of the Kelvin disk-and-wheel type, as illustrated in Figure 1. A top view of two associated integrator units is shown in Figure 7. In the design of the complete integrator every effort was made to take advantage of the light-beam system of transmission to obtain a freely running, stable, precision unit.

Since there is no mechanical connection between the integrator-wheel shaft and the output shaft, it is possible to move the integrator-wheel assembly in its carriage parallel to the lead screw rather than to move the entire turntable with respect to the integrator-wheel assembly. Thus, the axis of rotation of the turntable remains fixed in position, and the turntable is rotated by means of a simple right-angle

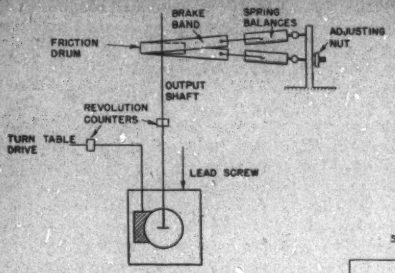

Figure 8. Mechanical integrator connections for slippage performance tests of Table I

The integrator output torque is adjusted by means of friction drum, brake band, and spring balances. Without slippage the revolution counters in the turntable drive and output shaft show a constant relationship

drive, no splined shafts being necessary. The lead screw for the integrator-wheel carriage is parallel to the directed light beams, so that, for any setting of the lead screw in the proper range of carriage travel, the light beams always will be directed properly through the optical system.

The integrator-wheel assembly is mounted in a pivoted support which permits free vertical movement of the wheel, thus assuring that it will remain in contact with the plate-glass disk. The wheel is of stainless steel, two inches in diameter, with a rim having a $^1/_{32}$-inch radius of curvature. Only a light pressure is required between the wheel and turntable, because, regardless of output-shaft load, all that is needed is sufficient friction force to turn the light integrator-wheel-shaft assembly in its jeweled bearings. The carriage is, thus, merely a guide for the almost frictionless balanced integrator wheel. Statically, there is very little pressure on the jeweled bearing surfaces; dynamically, there is pressure depending upon acceleration, principally, but this pressure is equalized between the two jeweled bearings because of the unique arrangement of counterweights.

Accurate alignment of the locus of the point of contact between integrator wheel and glass disk is maintained by means of ball-bearing contacts with guide rails. The vertical guide rail on the lead-screw side serves as the true guide, since the four ball bearings on this side (two making contact with the vertical guide and two with the horizontal one) are fastened rigidly to the carriage. The single bearing making contact with the horizontal guide on the side opposite the lead screw is also fastened rigidly to the carriage. Thus, the weight of the carriage is supported by three points of contact with the horizontal guide rails. The two ball bearings running on the vertical guide rail opposite the lead-screw side are spring supported on the carriage, thus causing the carriage to be held against the vertical guide on the lead-screw side.

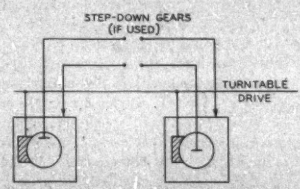

Figure 9. Mechanical interconnections of two integrator units for the generation of sine–cosine curves

This arrangement was used for the sine-wave growth tests of Table II

A lead-screw revolution indicator is shown in Figure 7, which is made up of two dials, one of which is graduated in hundredths of a revolution. The second is stepped down by means of gears to read complete revolutions over a range from +65 to −65. Thus, boundary conditions may be set to hundredths of a revolution. A split nut is pivoted in the carriage assembly and makes contact with the lead screw. Adjustable spring tension makes it possible to maintain the assembly free from back lash. A simple solenoid-operated clutch release is used which is positive in operation, and a push button is conveniently located so that boundary conditions can be set easily while the clutch is held in the released position.

Ventilating covers are provided for the thyratron tubes as shown in Figure 7. Screw adjustments for proper setting of the amplifier circuit constants are provided on the side of each unit.

Two limit switch controls on the integrator carriage are used in order to protect against possible overtravel and consequent damage. These are arranged in sequence, so that, as the normal range of travel is exceeded, the first switch stops the time motor. If travel of the carriage continues beyond this point; the second, which is an emergency switch, releases the clutch in the integrator lead screw.

Performance Data

The integrators were designed to operate at a maximum output-shaft speed of 1,000 rpm. One of the limitations on maximum permissible speed is that of slipping between the integrator wheel and the glass disk. In order to determine whether or not this was an important factor over the speed range up to 1,000 rpm, numerous tests have been made. The test set-up used for this purpose and for the purpose of determining the over-all mechanical accuracy is shown in Figure 8.

It will be recognized that, for each setting of the lead screw, there should be a fixed ratio between the number of revolutions of the output shaft and the turntable shaft. The revolution counters on these two shafts serve to add up the number of revolutions for each of these shafts and, when reduced to a common base of "equivalent revolutions" as required by the particular lead-screw setting, will serve as a means of evaluating the amount of slipping and over-all mechanical accuracy. For instance, since the lead screws have 16 threads per inch, and since the integrator wheel is two inches in diameter, there should be a 1:1 correspondence between the revolutions of the turntable shaft and the output shaft when the lead screw is set on either plus or minus 16. Thus, the integrator constant of

Figure 10. Control cabinets which house the power contactors, the regulated d-c power units for the amplifiers, the motor-driven field potentiometers of the Ward Leonard generators, and the two time-motor speed-indicating instruments

these devices is 16. Similarly, there should be just twice as many revolutions of the output shaft as of the turntable shaft when the lead screw is set on plus or minus 32, and so forth. Any difference between these nominal "equivalent revolutions" is due either to mechanical errors or slipping of the integrator wheel or both. Since any slip present should be a function of speed and acceleration, it seems reasonable to assume that, if there is no appreciable variation in the equivalent revolutions throughout the speed and load range, any deviation from a 1:1 correspondence based on equivalent revolutions is due entirely to mechanical errors and not to slipping. The test results summarized in Table I indicate that slipping does not exist to a measurable degree in these integrating units.

Another test which affords a measure of the over-all back lash of the follow-up system and connecting gear trains, an important criterion of performance, is shown in Figure 9. This system of connections will be recognized as that required for the solution of the harmonic equation

$$\frac{d^2y}{dx^2} = -\frac{1}{K^2G^2}Y.$$

in which K is the integrator constant and G is the gear ratio between the output shaft of each integrator. With one lead screw set on zero and the other at some arbitrary number of revolutions from zero at the start, if there were no back lash, the amplitude of succeeding cycles should equal this initial amplitude. However, because of the presence of back lash in the gears and follow-up system, the amplitude of successive cycles (number of lead-screw revolutions measuring displacement from zero) will increase. The rate at which this growth occurs in terms of revolutions per cycle is a measure of the over-all back lash and, therefore, serves as a good measure of performance. Typical sine-wave growth measurements of this nature are shown in Table II. Under the condition of high output-shaft speed and direct drive, the growth per cycle is most pronounced, as should be expected. As the step-down ratio is increased, the growth per cycle decreases rapidly and becomes relatively independent of integrator-wheel speed. The test results tabulated in Tables I and II were obtained with representative integrator units without the use of compensating means of any kind. When it is necessary to work with greater accuracies, suitable provisions can be made.

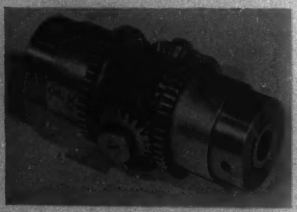

Figure 11. Representative adder unit

This low-friction design was found to require very small driving power

Control System

Speed control of the independent variable, ordinarily referred to as the time motor, is obtained by means of a Ward Leonard system which gives stepless speed control over the desired speed range, thus assuring the availability of optimum speed of operation at all times. The field potentiometer in the generator circuit is motor driven. This motor is controlled by means of push buttons at 12 convenient locations around the analyzer. A control panel is located at each input table and each pair of integrators. These panels include "start," "stop," "raise," "lower," and "reverse" buttons. They are so interlocked among the control stations that, if an operator at one station pushes a "lower" button, the time-motor speed will be decreased, even though operators at other stations may be pushing a "raise" button.

At each station there is also a two-position "hold" and "neutral" switch. If an operator cranking an input table requires that a certain time-motor speed not be exceeded, the switch is thrown in the "hold" position. The speed of the time motor cannot be raised then from any control station. It can be lowered, however, at any control station simply by pushing a "lower" button. Thus, the interlocking control system provides that the station requiring the slowest speed will always take control.

Whenever a "stop" button is pushed, and the time motor has come to a standstill, the motor drive for the generator field potentiometer automatically starts and brings the slider contact to the zero field potential position, thus assuring that, when an operator later pushes a "start" button, accelerations will not be excessive.

"Emergency stop" buttons are provided at convenient and readily accessible locations around the analyzer. By pressing this button all power to the analyzer, both alternating current and direct current, is removed. This serves to protect the machine against overspeed, and so forth, in case of a runaway or trouble, whatever its nature may be.

At each pair of integrators there is a push-button control for energizing the light source and tube filaments. This control has a time-delay relay which is interlocked with the a-c supply, so that voltage cannot be applied to the motor and thyratron circuits until five minutes have elapsed from the instant of energizing the filaments, thus assuring adequate heating time for the thyratrons.

Two separate time motors are provided, one at each end of the analyzer bed. This permits the simultaneous solution of two problems, provided that the total number of integrators or input tables required does not exceed those available.

The use of two time motors requires that the controls at each station be applicable to either of the two time motors, depending on which one is being used in conjunction with the integrators or the input table associated with that control station. In order to meet this requirement, all wiring for each time motor is in duplicate in the bed of the machine with two outlets at each control station, one for each time motor. By means of a jack-and-plug arrangement the control panel

Figure 12. General view of the differential analyzer from the input- and output-table side

There are four input tables and two output tables. The input-table drives may be cranked in both the horizontal and vertical directions. All input tables have polar co-ordinate attachments

Figure 13 (left). Top view of input table showing the polar co-ordinate arrangement

Figure 14 (right). Top view of output table showing the ink pen and the clear ink records

can be switched readily from one motor to the other as the requirements may dictate. This is shown in Figure 7, for example, applied to a pair of integrator units.

Figure 10 shows the control cabinets. They house the power contactors, the regulated d-c power units for the amplifiers, the motor-driven field potentiometers of the Ward Leonard generators, and the two time-motor speed-indicating instruments.

Miscellaneous Component Parts

A total of 20 differential gear assemblies or "adders" (one is shown in Figure 11) is available for use with the analyzer. These are of new design in which one of the major objectives was to keep friction to a minimum; this has resulted in light loads.

Helical gear boxes for right-angle drives are available. There are 50 right-hand and 20 left-hand drives.

Each input table (four are available) has both rectangular and polar co-ordinate drives. They can be used either as input tables for cranking in a function drawn in curve form, as manual multipliers, or as output tables for plotting solutions. Two output tables are located near the center of the analyzer. Each of these has two pencil carriages and will plot two functions simultaneously. The input and output tables are shown in Figure 12, and a close view of the input table arranged for polar co-ordinate drive is shown in Figure 13. Output-table records are obtained either by means of a fine-pointed brass stylus which is maintained lightly in contact with specially treated paper or by an inking pen. The ink records are easier to see and more permanent but do not permit as great accuracy in measuring. Figure 14 shows how distinct an inked output-table record may be.

Change gears totalling 440 are available in different tooth ratios required to give adequate flexibility to meet practically all needs.

Figure 15. General view of the differential analyzer

In the background are the two control cabinets, the wall-mounted master power switches, and the cabinet containing the induction-motor-driven Ward Leonard generators. The rack on the side accommodates all the accessories, such as gears, shafts, adders, and right-angle drives. The cabinet on the right of the accessory rack houses the air-conditioning system

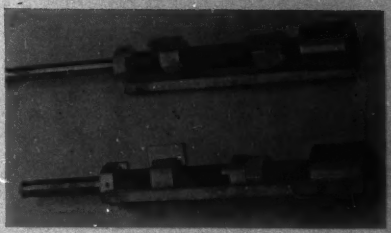

Figure 16. Adjustable "dead-band" units

The main bed of the machine is essentially the same as that for the analyzer at the University of Pennsylvania. It is approximately 32 feet long, and over-all width 9 feet. Fourteen steel pedestals support the analyzer. Each of these pedestals rests on the concrete floor to which all are bolted. Figure 15 shows a view of the complete analyzer.

The stub shafts were aligned by means of the screw supports on the bus-shaft housings. These screws are very helpful in initially aligning the shafts for minimum friction and binding. Once aligned, the adjustment remains stable, and further adjustment has been found unnecessary.

Two "dead-band" units (Figure 16) are available for the purpose of simulating intervals of no response or zero sensitivity, such as may be encountered in the solution of certain problems. Like those of the University of Pennsylvania, they are adjustable, so that the number of rotations of one shaft which can take place without the other one following it subsequent to a reversal of direction of rotation can be controlled. Once adjusted and inserted in the machine, the machine automatically includes the desired "dead band" in the solution.

Conclusion

Since the completion of this new differential analyzer several months ago, a number of important and urgent problems have been solved. The continuous

The MHO-Carrier Relaying Scheme

A Simplified Carrier Scheme for Long or Heavily Loaded Transmission Lines

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MEMBER AIEE

BECAUSE of the wartime problems of increased loads and shortage of materials, it is often necessary to put heavy loads on existing transmission lines rather than build new ones.

When transmission lines are heavily loaded it becomes difficult to retain relaying selectivity, because the currents and voltages which the relays measure are not sufficiently different to distinguish between faults and power swings except by adding auxiliary relays which check the rate of change of impedance. These auxiliary relays add complexity and cannot distinguish between power swings during which it is not desired to trip and an out-of-step condition for which it may be desired to trip.

This paper describes a new scheme which inherently distinguishes between the aforementioned swings and out-of-step conditions and, also, is very much simpler than its predecessors. It is based on the same principles as the "Long-line" relay scheme described in a group of papers[1,2,3] presented at the 1943 AIEE winter technical meeting, using phase-angle rather than impedance magnitude as a basis for distinction between load and fault conditions. It uses the same MHO unit, which measures admittance at about the phase angle of the protected line so as to provide a very high pickup on loads and power swings when set to operate on a fault at the end of the section. In this way the relays keep the transmission line in service as long as it can transmit power and remove it only when the systems swing apart so far that power cannot be transmitted.

Paper 44-46, recommended by the AIEE committee on protective devices for presentation at the AIEE winter technical meeting, New York, N. Y., January 24-28, 1944. Manuscript submitted November 10, 1943; made available for printing December 13, 1943.

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The authors acknowledge the assistance of the operation and engineering departments of the Tennessee Valley Authority and the central-station divisions of the General Electric Company in analyzing the relaying requirements of heavily loaded transmission lines.

Impedance Diagrams

In one of the aforementioned papers[2] it was shown that the locus of the impedance seen by a relay at a given location on a transmission line is a family of circles for different ratios of V_A/V_B where V_A and V_B are the terminal voltages at the ends of the line. The diameter of the circle tends to decrease as V_A/V_B departs from unity. It can be seen from Figure 1 that, if A were near the center of the system, V_A/V_B would decrease as the angle between V_A and V_B increased. Consequently, for a given system condition, the actual locus of the impedance seen by the relay at A during the progress of a power swing is a line joining the proper points of angular difference between V_A and V_B on the proper circles for varying ratios of V_A/V_B.

The difference between this new locus and the first family of circles is that the equivalent generator voltages E_S and E_R (Figure 1) are used instead of the line terminal voltages V_A and V_B. Since E_S/E_R usually is close to unity, the new loci will be circles of large diameter for different values of E_S/E_R; hence, usually it is permissible to dispense with the complex calculations of the rigorous method,

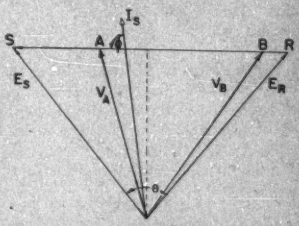

Figure 1. Vector diagram of a simple power system

and to consider all of the circles to be a single straight line passing through a point on the line-impedance vector separated from the origin by a distance approximately equal in ohms to the distance of the relay location from the electrical center. This is equivalent to assuming that the ratio of the equivalent generator voltages E_S/E_R is unity, and that there is no charging current or shunt loads. These simplifications have been used before,[4,5] and result in the following relatively simple determination of the power-swing locus on an impedance diagram. They are permissible here, because the availability of this analyzer will result in greater knowledge and better understanding of many other technical problems, solutions of which heretofore have been possible theoretically but impossible practically.

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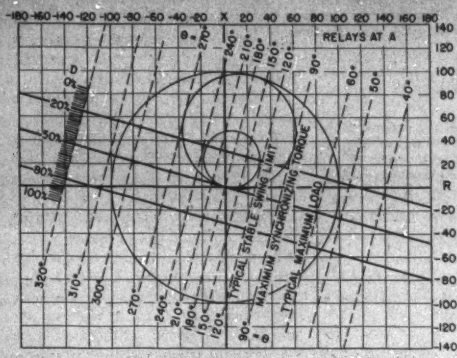

X/R = tan 75°
No shunt load
Shunt capacitance neglected
D = distance of relay location from equivalent internal voltage of the leading end E_S, in per cent of total impedance from S to R
The co-ordinates are scaled in per cent of total impedance from S to R; abscissas are resistance, ordinates are reactance

Figure 2. Impedance diagram for relays at various locations along a line connecting two systems, or machines, applicable to the special case in which $E_S = E_R$

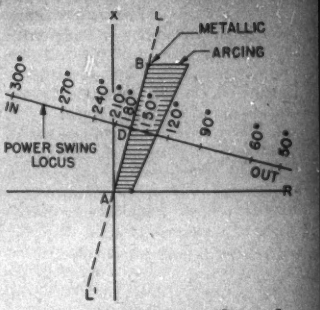

Figure 3 A. Resistance-reactance diagram of faults and swings

In = power incoming to bus
Out = power outgoing from bus

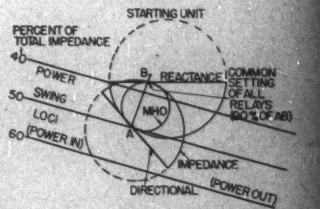

Figure 3 B. Characteristics of relays plotted on the R and X diagrams of a simple power system

possible inaccuracy is substantially tangential to the characteristic of the new relay and, hence, do not affect its setting.

The construction for obtaining the straight-line locus is as follows. Figure 1 is a simplified vector diagram of power transfer through a transmission line; it assumes that the power system has a uniform distribution of R and X and neglects capacitance. S–A is the impedance drop of the system behind the bus at the sending end of the line and R–B is the drop behind the bus at the receiving end. E_S and E_R are the sending- and receiving-end voltages which are assumed equal, and θ is the angle between them. I_S is the load current, and ϕ is the impedance angle of the transmission line. The input impedance at a point A is V_A/I_S which will change as θ changes. If V_A/I_S is plotted on an R and X diagram, it will appear as a straight line at right angles to the line impedance intersecting it at a distance from the origin equal to the distance of the point A from the electrical center. The vectorial equation of this line in terms of the angle θ between the generated voltages at the ends of the system is

$$\mathbf{Z}_A = \frac{\mathbf{Z}_S}{2}\left[(2D-1) - j\cot\frac{\theta}{2}\right]$$

where D is the per-unit distance of A from the leading end of the system (see Figure 2), and Z_S is the total impedance between the generator voltages E_R and E_S; $\mathbf{Z}_A$ and $\mathbf{Z}_S$ are vectorial quantities.

When faults are plotted on a similar R–X diagram along with the power-swing characteristic we obtain Figure 3 A. A fault appears instantly as a point on the line characteristic LL'. This line is at the angle $\phi = \tan^{-1} X/R$ where X and R are the reactance and resistance of the transmission line. Point B is at a distance from the origin equal to the impedance of the line section being considered. Point B is for a solid metallic fault at the end of the section and, since most faults are flashovers and involve arcs which introduce a resistance, this is represented by adding such a component horizontally, the shaded area being the fault zone.

Loads, power swings, and out-of-step conditions are represented as impedance having different R and X values which move inward along a line at right angles to LL' and cut it at a point D such that AD is approximately the distance of the relay location from the electrical center. The values of θ are marked along the power-swing line and it can be seen very quickly what degree of system separation appears as the same impedance value as a fault.

When the characteristics of the different types of ohmic relays are plotted on an R–X diagram, Figure 3 B is obtained, which shows that, for a given ohmic setting (90 per cent of line length AB) the reactance relay operates most readily, the impedance relay less readily, and the MHO unit much less readily than either. It can be seen that the MHO unit is simply a starting unit set for first-zone reach instead of third-zone reach.

When used with carrier blocking, however, it is apparent from Figure 4 B that the tripping area of the reactance relay is restricted considerably on power swings; out-of-step blocking, of course, prevents the distance elements from tripping in the horizontally shaded areas. In both cases, the electrical center has to be within the protected section to cause tripping, and tripping will only occur if the power-swing locus enters the tripping zones of the relays at *both* ends of the section. The carrier tripping area is shown shaded vertically in Figures 4 A and 4 B for the impedance and reactance relays. These diagrams are to the same scale, and illustrate that the tripping area is somewhat larger for the impedance relay because the radius of the characteristic determines the distance reach in the impedance relay, whereas only the diameter is involved in the case of the starting unit of the reactance relay.

Present Distance-Relay Carrier-Current Systems

It is apparent from Figures 4 A and 4 B that both of the present distance-relay–carrier combinations may limit unnecessarily the power that can be transmitted over a transmission line. The reactance relay limits this power by virtue of the fact that the starting unit must reach as far as is desired for the third-zone time step. The impedance relay, on the other hand, limits the load transfer because of the second-zone impedance unit, a type of relay unit that embraces more area on the impedance diagram than necessary.

The fundamental basis of the relay system herein described is the use of the starting unit of the reactance relay, but with its ohmic reach reduced to slightly greater than the line impedance, thereby encompassing a minimum area of the impedance diagram. A third-zone backup step may be obtained, if desired, by means described later.

To many operators, the principal objection to present-day distance-relay–carrier schemes is their complexity. The relay system to be described eliminates a substantial portion of this complication by establishing a group of "building blocks" which provides, in most applications, a simple relay scheme. For the more difficult applications, additions may be made without changing the fundamental relay scheme.

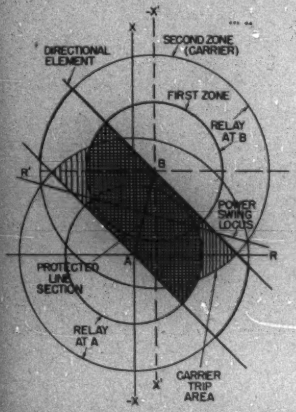

Figure 4 A. Impedance-relay characteristics plotted on *R* and *X* diagram so as to show combined tripping area

Vertically shaded area = carrier trip
Horizontally shaded area = distance trip

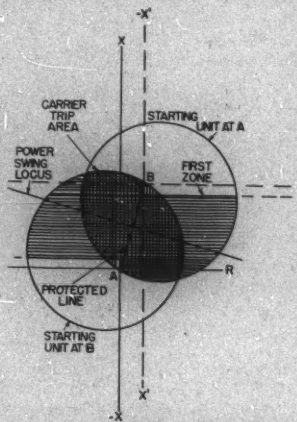

Figure 4 B. Reactance-relay characteristics plotted on *R* and *X* diagram so as to show combined tripping area

Requirements of the Ideal Scheme

Most of the requirements have been stated already in the previous paper on long-line relays.[3] A more complete list is as follows:

1. Trip instantaneously for internal faults, arcing or solid, including three-phase faults at the circuit-breaker terminals.
2. Trip in delayed time for external faults.
3. Provide carrier blocking for external faults.
4. Not operate relays or carrier on loads up to the steady-state power limit.
5. Control tripping on system oscillations according to a value of impedance, seen by the relay, which represents the maximum power-swing condition for which it is desirable to stay in.
6. Be flexible enough to provide blocking on out-of-step conditions which may make this desirable.
7. Clear instantaneously all internal faults occurring during power swings or immediately after an external fault. Trip after a time delay if out-of-step blocking is used.
8. Allow reclosing after tripping on a fault, but not after tripping on an out-of-step condition.

The value of impedance representing item 5 depends upon either the maximum angle which can be tolerated from a stability standpoint or the angle which can be tolerated because of other limiting system conditions, such as low voltage.

Items 1, 3, 4, 5, and 7 are inherent in this scheme; item 2 may be achieved by backup relays as discussed later, and item 8 is accomplished by using the rate of change of impedance for blocking the reclosing circuit instead of the tripping circuit. A more detailed explanation of the operation of the relays now follows.

Characteristics of New Scheme

The original carrier-current idea[4] was a very simple one, consisting of only a pair of directional relays which started carrier for external faults and made up a trip circuit for internal faults. This scheme returns to that idea in that it has but two relay elements—one for starting carrier, and one for the trip circuit.

The basic circuit is shown schematically in Figure 7. It will be realized, of course, that certain liberties have been taken in order to present the circuit in its simplest form for purposes of explanation.

The unit *Z* starts carrier for all phase faults by opening the carrier-start lead, and the unit *M* turns off carrier if the fault current is flowing into the section and completes the trip circuit up to the receiver-relay contacts. Then the removal of carrier current from the receiver relay allows it to trip the breaker.

A ground fault in the reverse direction opens the contacts GD_1, starting carrier and causing the contacts *R* to remain open and prevent tripping. A fault in the tripping direction closes the contacts GD_2 to complete the trip circuit up to the receiver relay, which trips because no carrier is started.

The connections actually used are illustrated in Figure 8, and the operation of the relays is described in the following section.

Operation

A. Phase Faults

Each phase has an impedance relay for initiating the carrier signal under abnormal conditions by circuit-opening contacts Z_1, Z_2, and Z_3, Figure 8. This characteristic is shown as the circle *Z* in Figure 5.

An impedance element was selected for starting carrier because it will operate on power swings as well as faults. It has

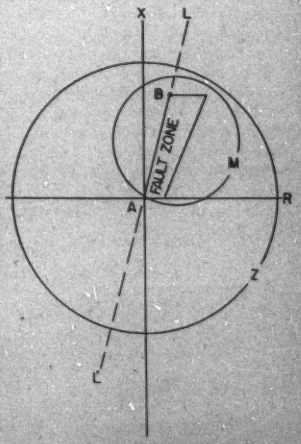

Figure 5. Characteristics of the MHO-carrier relaying scheme

M defines the tripping zone; *Z*, the carrier-starting zone

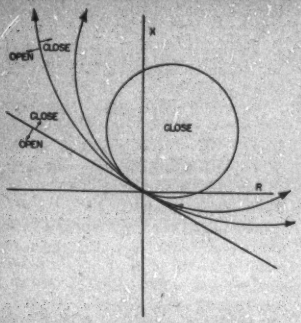

Figure 6 A. An impedance diagram illustrating how the straight-line characteristic of a directional relay becomes a circle as voltage restraint is added

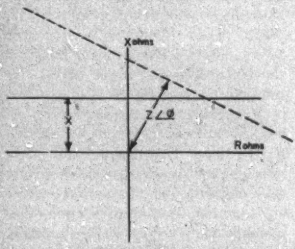

Figure 6 B. An R–X diagram of a reactance unit ($Z/90°$) and an ohm unit (Z/ϕ)

Reactance unit—solid line
Ohm unit—dashed line

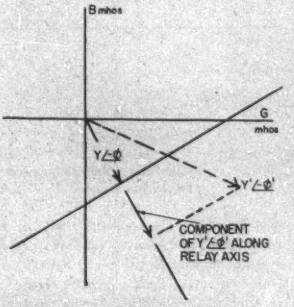

Figure 6 C. A G–B diagram of a MHO unit ($Y/-\phi$)

the advantage of being available, on medium-length lines, for preventing tripping or reclosure on out-of-step conditions. It can also be used for controlling a timing unit for backup purposes if the stepped distance-type backup is desired.

The second, or tripping, element in the relay scheme is an admittance element, called, for short, a MHO unit, since admittance is expressed in mhos; its characteristic is shown by circle M of Figure 5. This unit has been known for many years as the starting unit of the reactance-type distance relay.

A MHO unit is a directional element with voltage restraint added. As a directional element, it has maximum torque at some particular angle. As such, its characteristic is a straight line, as in Figure 6 A, operating to open contacts to the left of the line and to close them to the right. The addition of voltage restraint curls up the ends of the straight line into a circle, the size of which becomes smaller as the restraint is increased.

Each phase has a MHO unit, M_1, M_2, and M_3, which stops carrier through an auxiliary relay MX and makes up the trip circuit through a carrier-current receiver relay R, if the fault is within the protected section. In this respect the scheme is similar to earlier equipments.

B. Ground Faults

The ground relaying has been considerably simplified by a return to the original idea of back-to-back directional relays, which is permissible for ground relays because there is no complication of power-swing currents entering at right angles to the fault currents. There is a complicating factor in the ground relaying, however, namely, the now known fact[7] that residual currents can appear in the current-transformer circuits for phase faults not involving ground. These undesirable stray currents occur because the current transformers do not balance out perfectly, and this, in turn, is primarily the result of premagnetization of the core, not to mention differences in manufacturing tolerances, et cetera. The usual settings require current transformers to be within less than one half of one per cent of each other, which is a severe requirement.

The use of a directional relay for starting carrier requires simultaneous errors of the proper phase angle of the polarizing source, as well as of the line current transformers, before a false operation can occur, since it operates on a product of the residual current of the three line current transformers and the polarizing voltage or current. With directional fault detectors throughout, no preference need be given to either the ground or phase relays. The idea of preference arose originally because the ground relaying had to be more sensitive than the phase relaying, and it was feared that load or power-swing currents would take control unless the ground were given preference. It has been dispensed with now, because years of experience have indicated that false residual current may be produced by magnetized current transformers during phase faults, which may operate the ground overcurrent relay which turns on carrier and prevents tripping.

Carrier is started by a ground directional relay GD_1 (Figure 8) with normally closed contacts, which open for faults in the backward direction and remain closed for faults in the forward, or tripping, direction. The trip circuit is made by a similar directional relay GD_2 connected just oppositely with normally open contacts.

Settings of the Z and MHO Units

The impedance relay may be set to reach beyond the end of the line as long as it does not exceed the impedance value (see Figure 2) corresponding to maximum steady-state load. On short lines there will be no possibility of this, but on very long lines it is advisable to confine the relay setting to the line-section length, in order to avoid having carrier on for long periods. Reference to Figure 2 will show that, if the line could contain all the system impedance, the relay characteristic would reach to some point between the 50- and 60-degree lines which represents about the maximum separation that would be considered for steady-state conditions.

The MHO unit controls tripping, and, therefore, should not operate on power swings from which the system can recover. As stated before, the actual ohmic value representing this borderline depends upon system conditions, but it is known that above 90 degrees difference between the equivalent generator voltages the synchronizing power will decrease so that, while they may swing almost 180 degrees apart and still be stable, the limit is some value nearer 90 degrees.

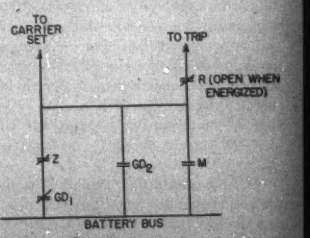

Figure 7. Simple elementary diagram of the MHO-carrier relaying scheme. The carrier starts when the circuit is opened and stops when the circuit is closed

See subcaption of Figure 8

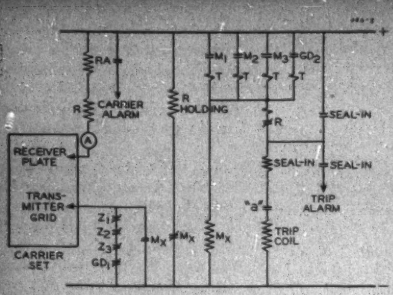

Figure 8. Complete elementary diagram of the MHO-carrier relaying scheme

A = ammeter
GD_1 = ground directional relay (blocking)
GD_2 = ground directional relay (tripping)
M_1, M_2, M_3 = MHO relay units in phases 1, 2, and 3
MX = MHO auxiliary relay
R = receiver relay
RA = receiver alarm relay
T = target
Z_1, Z_2, Z_3 = impedance-relay units in phases 1, 2, and 3

With all the system impedance in the line, if the MHO unit has maximum torque at the same angle as the line and is set to just cover the line, it will reach about the 90-degree separation line; if the line impedance is half the total impedance, it will reach to some point between the 120- and 130-degree lines. It can be seen from this that, on short lines and most long lines, the MHO unit will trip for faults and out-of-step conditions, but not power swings. On very long, very heavily loaded lines, some form of "blinders" will be required, such as the ohm units used in the long-line scheme,[1] which measure the component of impedance along the locus of the power swing so as to prevent tripping below a certain angle of system separation determined by a system study.

It will be seen from the foregoing that an application engineer can determine relay settings readily, as soon as he has decided the limits of steady-state load and the maximum angle permissible for power swings.

Description of Relays Used

A. The Phase Relays

Impedance Fault Detector. The characteristics of this relay often determine the maximum length of line that can be protected with this system of relaying. The longer the line, the less difference there will be between the impedance of a remote fault for which the relay should operate and the impedance for load conditions for which the relay should reset. In other words, the pickup of the relay and the dropout current should be as near together as possible.

The impedance unit Z used is of the induction-cylinder-type construction, using all eight poles to obtain a torque proportional to the operating current. This torque is perfectly smooth, free from any 60-cycle vibration—an inherent feature in the induction-cylinder construction.[8] This feature is necessary because the unit

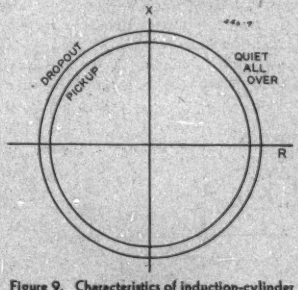

Figure 9. Characteristics of induction-cylinder impedance relay

may remain in the operated position for considerable periods of time when the systems are exchanging power at near the stable operating limit. Voltage restraint is provided by an attracted-armature-type construction with an adequately smoothed pull. This type of construction gives the most force for the least volt-ampere burden—practically a requirement for an impedance relay. Such a relay is seriously limited in this respect because the potential coil must stand rated voltage continuously and yet, when it is called upon to operate, must do so with only a small percentage of normal voltage. The usual disadvantage of an attracted-armature construction is that the force diminishes rapidly as the gap increases, being higher than the second power of the gap. This is minimized by operating with an air gap several times as large as the contact gap, and by using the minimum number of contacts; namely, a transfer contact giving one normally closed and one normally open contact. By this means, the unusually high drop-out of over 90 per cent of pickup is obtained, Figure 9.

The MHO Tripping Relay. The MHO unit has the same four-pole induction-cylinder construction employed in the *GCX* directional distance relay, producing an operating torque proportional to $EI \cos (60° - \theta)$ and a restraint torque proportional to E^2. The angle of 60 degrees was selected as being near, but generally smaller than, the natural angle of a transmission line in order to minimize the tripping zone for power swings as explained under "Operation."

One of the most important features of the MHO unit is its memory action. No directional relay is expected to function with zero voltage, and this is the condition at which the mho circle passes through the origin. This difficulty is circumvented by making the polarizing potential circuit resonant at 60 cycles, so that the coil continues to have a substantial voltage across it for several cycles after the line voltage has been reduced to zero by a fault close to the bus. This feature cannot be shown on the two-dimensional R–X mho circle diagram, but, if polarizing torque were plotted in a third dimension, it would have a sharp peak near the origin.

The MHO unit has double-wound current coils which give the same reach on phase-to-phase as on three-phase faults.

Origin of the Term MHO Unit. Why is the unit called a MHO unit? This sounds complicated, but we believe that it is actually the simplest name possible. The characteristic of the MHO unit is the circle of Figure 6 A, and whereas this shows graphically where the relay operates, there is no expression which states what the relay operates on. For 15 years we have had a reactance ohm unit which has the characteristic of the horizontal straight line in Figure 6 B. This unit operates whenever the reactive component of the impedance, measured in ohms, is less than its setting X. This character-

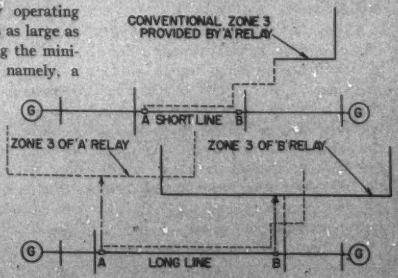

Figure 10. Tripping zones illustrating conventional and nondirectional long-line backup

istic can be tilted as shown by the dotted line, and then the unit operates whenever the ohmic component along the perpendicular line through the origin is less than the setting of Z/ϕ. Now, the MHO-unit characteristic is a straight line when plotted on an admittance diagram, as in Figure 6 C, and this immediately shows that it operates whenever the component of the admittance Y at the angle ϕ is greater than the relay setting.

B. Ground Relay

The ground directional units are likewise of the induction-cylinder construction available with either current or potential polarization. Their torque is proportional to the product of the two currents or to the current and the voltage, so that false operation would require an error in the polarizing source as well as a false residual current resulting from unequal current-transformer action. The lack of response to the d-c component of offset waves is an already well-known feature of the induction principle.

C. Receiver Relay

A conventional permanent-magnet polarized receiver-relay unit is employed. It has spring-closed contacts and two restraining windings, one energized from the local battery, and the other energized by carrier received from either end of the line.

Usually, the first winding is energized through back, or normally closed, contacts of the mho-auxiliary unit *MX* in Figure 8, and holds the receiver-relay contacts open. When a fault occurs, the fault detectors turn on carrier, energizing the second winding by the carrier-receiver plate current. If the fault is within the protected section, the phase or ground directional relay *M* or *GD* shuts off carrier and de-energizes the battery winding so that the spring-operated contacts of the relay close and trip the breaker.

The advantage of this arrangement is that the second winding, the so-called d-c holding coil, keeps the contacts open until the trip circuit is completed. This coil is energized for reverse faults, thereby providing double assurance of preventing tripping.

Backup Protection

Backup protection is being considered separately because opinions differ as to the best type of relays, but almost everyone agrees that the backup relays preferably should be self-contained and separate from the carrier relays.

This is most easily achieved with the ground relays for which the standard residual product or directional residual-overcurrent relays are very satisfactory. In the case of the phase relays, either directional overcurrent relays or stepped distance relays can be used, but in either case a MHO unit should be used for directional purposes, except in the case of very long lines on which the 20-degree ohm-unit blinders[1] are used.

The standard two- or three-step distance characteristic can be provided, though with some loss of simplicity of the scheme. The first step may be a standard reactance ohm unit set for 90 per cent of the protected section, using the MHO unit of the carrier-relay group as a starting unit; or it may be an entirely separate MHO unit, set for 90 per cent of the line and connected directly to the trip coil so as to provide a very reliable emergency trip of the utmost simplicity. The chief purpose of the zone-1 distance step is to provide protection when the carrier equipment is out of service for maintenance.

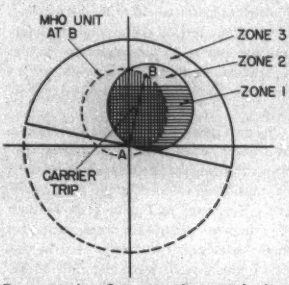

Figure 11 A. Conventional zone-3 backup for a short or medium-length line showing zones of protection provided by breaker A

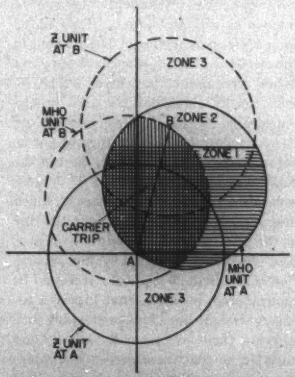

Figure 11 B. Nondirectional zone-3 backup for a long line, showing zones of protection provided by breaker-A relays and supplemented by breaker-B relays

Note that the zone-3 circle is the same size as Figure 11 A, which is determined by the maximum-load transfer. All the enclosed area represents protection

In an emergency, instantaneous tripping on internal faults can be obtained while the carrier is out of service simply by short-circuiting the receiver-relay contacts with the carrier cut-off switch in the "off" position. This will enable the MHO unit to give instantaneous protection with carrier off; the fact that it is set for 110 per cent of the line ohms may not be as important as it sounds because, if there is generation on the bus, the actual reach in miles may be only one or two per cent beyond the end of the section, and the chance of a trip on an external fault in that small section would be very remote. If immediate reclosing is available, its significance almost disappears.

The second and third zones can be provided by a timing unit controlled by the impedance relay. The zone-2 contact is connected in parallel with the receiver relay so that, if the latter does not operate, such as when the fault is just beyond the bus but within the mho-unit range, the breaker will be tripped after a short delay.

On very long lines it is difficult to make the third zone reach far enough to do much good as backup, particularly if there is generation at the next bus. In such cases the relay nearer the fault can be used for zone 3, as shown in Figure 10, so that the voltage restraint on the relay is less by the drop in the line. The upper part of Figure 10 shows the usual arrangement of the time steps of distance relays and the lower part shows how the third step can be provided by the relay near the fault. The appearance of the relay characteristics to achieve this result are shown in Figures 11 A and 11 B, respectively.

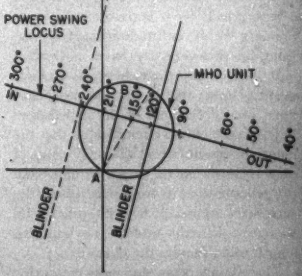

Figure 12. Blinders permit power swings to enter the MHO-unit circle

Note that the 60-degree MHO circle requires but one blinder on a 75-degree line

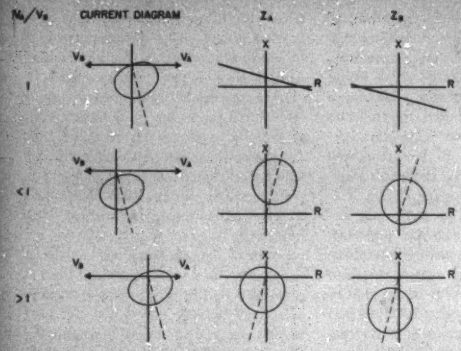

Figure 13 A. Characteristic loci of impedance as seen by relays during a power swing for different ratios of V_A/V_B

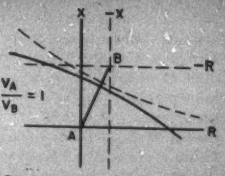

Figure 13 B. Locus of swing impedance viewed from the two ends of a transmission line

The solid line is seen from *A* and the dashed line from *B*

This simply means having the third-step timer contact going directly to the trip circuit and not controlled by a directional unit. The range of the third step, therefore, will be the ohmic setting of the impedance relay, which, on a long line, will be something less than the length of the setting. Thus backup time will be provided for external faults behind the bus and, also, over part of the protected section.

Very Long Lines

Figure 2 shows that the impedance seen by the relay during a swing decreases as the systems get farther apart until a point is reached where the relay characteristic is crossed and the tripping occurs. Since the size of the relay characteristic increases with the length of line covered, it can easily be seen that the tendency of the relays to trip during power swings increases with the length of line and the magnitude of the power swing.

Lines which are so long, or so heavily loaded, or both, that the line impedance during power swings is low enough to operate the MHO unit, require additional relays, which have been referred to as blinders, to prevent undesirable tripping. Lines in this category have more than half the total impedance between the ends of the system; that is, the line impedance must exceed the sum of the impedances beyond each of its extremities, so that the length of the line from the relay point of view depends on its length in miles and the generation at its terminals. Actually, such lines are usually over 200 miles long, though a heavily loaded line half this length could require the blinders.

These blinders are ohm units measuring a component of impedance along the power-swing locus, that is, about at right angles to the line characteristic.

These units have been described elsewhere in detail.[1] They are similar to the standard *G–E* reactance-relay ohm unit except that they measure impedance at 20 degrees lead instead of 90 degrees lag. Their ohmic setting corresponds to a certain amount of load transfer or system separation, so that they may be set to trip on a power swing of a desired magnitude.

In some cases it is desirable to permit a separation of more than 120 degrees between the generated voltages when they are considered lumped at the ends of the line. Reference to Figure 2 shows that 120 degrees separation represents an ohmic value equal to 29 per cent of the total impedance between the ends of the system, which means that a MHO unit with maximum torque at the same angle as the line phase angle must not be set to cover more than 58 per cent of the system impedance without blinders; if one allows for a MHO-unit setting of 110 per cent of the section, the impedance of the protected section must not exceed 58/110 = 0.52, that is, about half the total system impedance. If 150 degrees is considered the criterion, the MHO unit must not be set to cover more than 28 per cent of the total system impedance. For 90 degrees separation the figure is 100 per cent, which means that, no matter how long the line is, the MHO unit will not trip on swings or load conditions causing a system separation of less than 90 degrees. It should be remembered, however, that Figure 2 assumes straight lines for power-swing loci, whereas they are generally curves and variable, so that these percentage values are only approximate.

The corresponding figures for the impedance relay are half those of the MHO unit because the radius of the impedance-unit circle gives the same ohmic, or distance, setting as the diameter of the MHO unit. In other words, the impedance unit must be set for not more than half the ohmic reach of the MHO unit in order to avoid operation on swings.

The minimum ohmic setting of the blinders is the maximum arc resistance expected. This can be understood readily by reference to Figure 3 A. The maximum arc resistance[2] is 8,750 $L/I^{1.4}$ where I is the current in amperes and L is the arc length in feet. For a 154-kv line the spacing will be about 14 feet and, if allowance is made for a light wind, the arc length may be 2 feet; at 500 amperes minimum current this would give an arc resistance of $8{,}750 \times 20/6{,}000 = 29.2$ ohms. Compared with this, a 100-mile line would have an impedance of about 80 ohms, but, of course, at a highly lagging angle.

It is sometimes unnecessary to use two sets of blinders, that is, six ohm units for preventing tripping or power flow in either direction. Usually only one set of three ohm units is required because it is generally possible to have the angle of the MHO unit less lagging than that of the line, so that the relay may be vulnerable only in the direction of outgoing power, as shown in Figure 12.

Reclosing

Many of these long and/or heavily loaded lines are the lines between systems or parts of a system whose loss may result in the loss of other ties. Hence instantaneous reclosing after clearing faults may often be the means of saving the stability of the system.

It is preferable, however, to reclose only after faults and not after tripping on power swings or out-of-step conditions, because in the latter case the system is liable to be too far apart to stay in when reclosed. When a swing occurs it is caused by an abrupt change in load, generally an increase in load due to the loss of a source of generation. Reclosing is undesirable if the new load is greater than the load that can be reclosed successfully, that is, with stability after reclosure.

This selection of conditions suitable for

reclosing therefore can be made on the basis of the ohms along the power-swing locus representing the maximum steady-state load. A blocking relay with this ohmic setting can pick up an auxiliary relay with a slight delay which will prevent reclosing unless it is de-energized by the tripping relay before the auxiliary has had time to pick up, as would be the case of a fault where the blocking and tripping relays would operate simultaneously.

On short and medium-length lines the impedance relay that starts carrier can be used, also, to energize the auxiliary relay for blocking reclosure, because the impedance relay can always be set higher in ohms at any angle than the MHO unit which controls tripping and which can be used, also, for preventing the blocking.

On very long lines the impedance unit may not pick up before the MHO unit, and, in fact, both may be rendered ineffective by blinders. In order to ensure proper operation, in such cases, an additional single-phase unit is required to pick up the auxiliary relay and it must be of the same type as the tripping relay but with a higher ohmic setting. If the tripping relay is a MHO unit, the blocking relay must also be a MHO unit, so that it will pick up before the tripping MHO unit under all conditions. Similarly, if tripping is limited by a blinder, the blocking relay also must be an ohm unit like the blinder, but set for higher ohms. There is always a margin between the two like units, because the tripping unit must be set below the ohms of the maximum power swing, whereas the blocking unit has only to clear steady-state load conditions.

Where stepped-distance backup is used, the distinction often can be made very simply by arranging to reclose only after tripping by carrier relays. The line must be short enough to permit the impedance unit to be set farther than the MHO unit, so that carrier blocking will be available on all power-swing conditions where the electrical center is within the protected section. In that case power swings will trip through the first-step MHO or reactance unit and will not reclose, whereas a fault will energize the carrier-relay trip circuit, also, and operate an auxiliary relay which will initiate reclosing.

Conclusions

The new scheme has a direct approach to the problem of relaying heavily loaded transmission lines, and has the virtue of considerable simplification over previous schemes.

It is applicable to all lines which normally would be considered long enough to justify the cost of carrier relaying.

Appendix

The following is a pictorial explanation of why the impedance loci appear as circles for a given ratio V_A/V_B. It has been explained already under "Impedance Diagrams" how the straight lines in Figure 2 are obtained for the condition $E_S=E_R$ and no shunt impedances. Figure 13 A shows a series of diagrams representing the loci Z_A and Z_B at stations A and B in Figure 1, A being at the leading, or sending, end of the transmission line AB.

The current diagrams[4] would be circles if all the impedance were in the line, that is, if bounded by infinite busses. As the relay location approaches the electrical center the current locus approaches a semicircle. The voltage locus, however, has a complementary shape, so that the impedance becomes a circle.

In these diagrams capacitance has been neglected, but it can be seen easily that capacitance will tend to curl the straight lines for $V_A/V_B=1$ downward, because they would tend to pass through a point on the $-X$ axis when V_A and V_B were in phase, so that the only current was charging current. Hence the effect of charging current would be to make all the circles below the R axis smaller and those above it bigger. For that reason the circles Z_A and Z_B would not be exactly symmetrical with respect to each other. In other words, if Z_A and Z_B were plotted on the same diagram, as in Figures 4 A, 4 B, and 13 B, the two loci would not coincide because of the effect of capacitance.

In the preliminary diagrams of Figure 13 A, small circles are shown because V_A/V_B and V_B/V_A are large. Actually, the ratio would seldom exceed 1.25 and the circles would have a very large diameter, so that the part in the region of the power swings and the relay characteristics is more nearly a straight line.

A great deal of work has been done on graphical and analytical methods of obtaining the power-swing impedance loci. A quick method[10] is to obtain the line impedance in the form of the equivalent T, and to calculate directly from it the radius and the ordinates of the center of the circle for the required ratio of V_A/V_B by vector algebra.

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Effect of Altitude on Impulse and 60-Cycle Strength of Electrical Apparatus

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ALTITUDE is accompanied by a lowering of the air density, and, accordingly, it affects the performance of electrical apparatuses which depend on the air for operation. Thermal performance is affected because of the reduced heat dissipated by convection. Similarly the dielectric strength suffers a decrease with lower air density. The windage losses of machines and damping of instruments are less, but, in either case, the amount is not of consequence. At very high altitudes commutation may present a major problem and storage batteries become affected adversely. The interrupting capacity of some circuit-interrupting devices is also affected, the amount depending on various conditions. These are well-known instances where altitude is a factor in the operation of electrical apparatus.

Much research activity has been directed to these problems. From the beginning of high-voltage transmission, altitude was recognized as a factor affecting the operation of line and station apparatus.[1] Repeated efforts have been made to determine corona loss, and, to this end, several investigations have been conducted on transmission lines at high altitude.[2-4] Contributions on the dielectric strength of air[5,7,4] and of electrical apparatus[8] at normal and low air densities date from this early period. Similarly the effect of low air density on the thermal characteristics of electrical apparatus has been the subject of comprehensive investigations both from an engineering[9-14] and a fundamental approach.[15,16] The physical aspects and other practical considerations of the problem[17-21] have been examined from time to time. As far as feasible the results of this work have found expression in the various apparatus standards and test codes.

Certain fundamental data are still lacking although much progress has been made. This fact has been brought out in the Pacific Coast AIEE conference on the "Effect of Altitude on Rating, Testing, and Operation of Electrical Apparatus" in conference papers presented by P. L. Bellaschi, L. W. Robertson, and V. M. Montsinger and elsewhere.[22] For instance, an immediate need is for impulse and 60-cycle data on actual station and line apparatus at low air densities corresponding to high altitude. This need has been recognized for some time, and the results of this investigation should therefore be timely and helpful in the field of application at high altitude.

Test Setup and Apparatus Tested

The tests were made in a sealed Micarta cylinder, 30 inches in diameter and 60 inches long inside. The test setup is shown in Figure 1. Either end of the cylinder may be removed, the apparatus for test enclosed, and the vacuum drawn. At the desired air pressure, voltage is applied to the high-voltage terminal which enters the cylinder at one end, the second terminal at the other end connecting to ground. A valve is set to leak air into the cylinder at a rate equal to the air removed by the vacuum pump; thus the air circulates through the cylinder and the inside pressure is maintained constant. Instruments give the essential data on the air. A barometer and a manometer provide measurements of the air pressure in the cylinder and outside. Wet and dry bulb thermometers measure the humidity and a thermocouple thermometer the temperature in the cylinder.

The tests cover some of the more common apparatus encountered in stations and on lines. These are listed in Table I. Figure 2, for instance, shows 15-kv and 69-kv bus and switch insulators typical of the standard apparatus that have been tested. Figure 3 illustrates a six-unit insulator string in the process of being lowered in the cylinder for test. The arrangement in Figure 4 for enclosing a 69-kv bushing indicates the flexibility of the Micarta cylinder in conducting the tests on the various station and line apparatus. In part of the tests as on the wood crossarm, shown in Figure 5, a porthole window was available at the ground end of the cylinder for visual observation of corona, flashover, and other effects. The smaller apparatuses were fitted with terminal electrodes in the manner prescribed in the usual dielectric tests. For large apparatus the clearance was limited, but in no instance did flashover occur other than over the apparatus or in the air. Thus the tests truly and effectively were on the apparatus proper in a reduced atmosphere.

Method of Test

The procedure was to adjust the air density in the cylinder to the desired value and to condition the apparatus and the cylinder to the "new altitude." We found that for most apparatus the time required for the pumping sufficed to

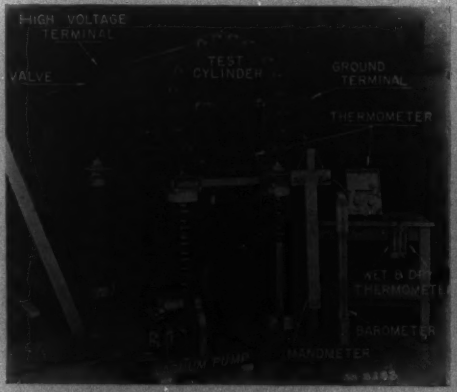

Figure 1. View of test setup

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Table I. *RAD* Investigation of Station and Line Apparatus

Apparatus Tested	Type	Impulse Tests: 1½x40 Microseconds, Positive	Impulse Tests: 1½x40 Microseconds, Negative	Impulse Tests: 1,000 Kilovolts Per Microsecond, Positive	Impulse Tests: 1,000 Kilovolts Per Microsecond, Negative	60-Cycle Tests
15-kv switch and bus insulator	Station (outdoor)	X	X			X
*69-kv switch and bus insulator	Station (outdoor)	X	X			
69-kv condenser bushing	Station (outdoor)	X	X			
6-unit 10-inch-diameter suspension insulator	Station and line	X	X			
15-kv dry-type current transformer	Station (indoor)	X				
15-kv apparatus insulator	Station (indoor)	X	X			X
15-kv air-insulated transformer (Model)	Station (indoor)	X	X			X
8.66-kv air-insulated transformer (Model)	Station (indoor)	X	X			X
66-kv crossarm, four-foot section	Line	X	X			
6- and 12-inch rod gaps	General	X	X	X	X	
24-inch rod gap	General	X	X			
½-inch transformer oil (gap)	General		X			

condition the apparatus and the cylinder. In some tests, as on the transformer oil, constant air density was maintained several hours previous to the test. As stated before, a leak valve in combination with the vacuum pump provided a continuous flow of the air at constant pressure in the cylinder.

Tests were made from normal to low air densities and vice versa, with practically the same results. Most test data are limited from 1.00 to 0.50 relative air density (*RAD*), as this covers the practical range in altitude encountered on the earth's surface (Table II). However, some tests were extended below 0.10 *RAD* which corresponds to well above 40,000 feet and a few up to 1.50 *RAD*. All tests were made at room temperature, 20 to 30 degrees centigrade, and at 890 feet (Sharon, Pa.).

The data are reported in terms of the relative air density, given by the formula

$$RAD = \frac{0.392\ b\ \text{(millimeters)}}{273 + t\text{(degrees centigrade)}}$$

in which b is barometric pressure and t is temperature. The absolute humidity at the low *RAD*'s is, essentially, the absolute humidity at atmospheric pressure reported for each series of tests multiplied by the *RAD*. The reason for this lies in the fact that for a given mass of air, the water content is the same inside and outside the cylinder.

The technique of testing and measurement fully complies with the recognized methods described in AIEE Standard 4 (1943). In this respect the Sharon high-voltage laboratories are well equipped for both 60-cycle and impulse testing. For instance, an impulse generator of 0.016 microfarad at 3,000 kv and correspondingly higher capacitance for lower test voltages was available. All impulse measurements were recorded with the cathode-ray oscillograph. Typical oscillograms are shown in Figure 15.

Full-Wave Impulse Tests

The critical flashover data for 69-kv and 15-kv switch and bus insulators are plotted in Figure 6. Each point represents the crest of a 1½x40-microsecond voltage impulse which caused flashover on 50 per cent of the applications. From normal to 0.47 *RAD*, the lower limit of these tests, each set of points practically determines a straight line. The voltage over this range is directly proportional to the *RAD* plus a constant. One curve extends to 1.23 *RAD* which at 760-millimeter barometric pressure would correspond to −51 degrees centigrade. These curves are typical of the tests made on other outdoor station apparatus and on line insulators.

One point of interest is the longer time to flashover observed at low air density.

Figure 2. Typical switch and bus insulators tested

A. Apparatus insulator, 15-kv class, indoor type

B. Switch and bus insulator, 15-kv class, outdoor type, National Electrical Manufacturers' Association standard

C. Switch and bus insulator, 69-kv. class, outdoor type, NEMA standard

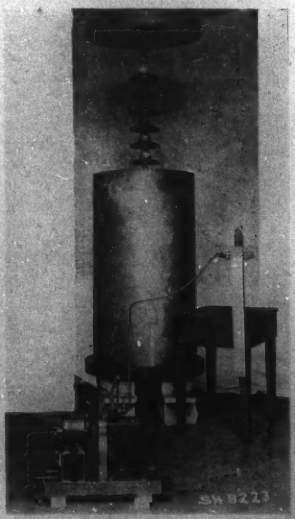

Figure 3. Test arrangement for suspension insulators

Insulator string being lowered into cylinder for test

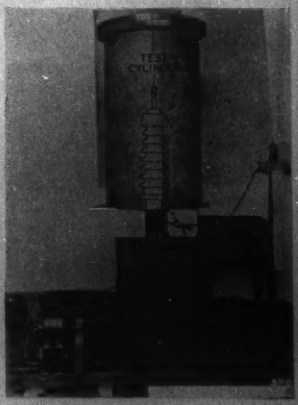

Figure 4. Test arrangement for bushing

Table II. Atmospheric Conditions at Various Altitudes

Elevation		Standard Atmosphere*			Isothermal** Atmosphere	Conditions on Earth's Surface	
				$RAD = \frac{0.392b}{273 + t}$	Temperature = 0C		
Feet	Meters	Barometric Pressure (Millimeters)	Temperature (Degrees Centigrade)		Barometric Pressure (Millimeters)	Temperature† (Degrees Centigrade)	Humidity Vapor Pressure (Millimeters)‡
0	0	760	15	1.03	760	20	15.45
3,281	1,000	674	9	0.94	670	10	10.60
6,562	2,000	596	2	0.85	592	7	7.40
9,843	3,000	526	−5	0.77	522	2	5.10
13,120	4,000	462	−11	0.69	461	−3	3.50
19,690	6,000	354	−24	0.56	359	−14	1.70
26,250	8,000	267	−37	0.44	280		
32,800	10,000	198	−50	0.35	218		
39,370	12,000	145	−55	0.26	169		
49,210	15,000	90.7	−55	0.16	116		
65,620	20,000	41.4	−55	0.075	60		

* National Advisory Committee for Aeronautics reports 218 and 538.

** Smithsonian Meteorological Tables, numbers 56 and 57.

† Reference 20, "Mean Temperature for the Entire United States."

‡ References 17 and 19, typical data for standard reference (15.45 millimeters, vapor pressure) at the earth's surface.

In Figure 15 are typical oscillograms. Thus, for the 69-kv bus and switch insulator and a negative wave, the time to flashover at 0.97 *RAD* is seven microseconds and at 0.47 *RAD*, 27 microseconds. Present concepts of the breakdown mechanism appear to be in accord with this effect.

The tests in Figure 7 were made on a 15-kv dry-type current transformer rated 100/5 amperes. This apparatus depends for its strength on tape or layer insulation in combination with the air. Flashover determines the insulation level. The curve is typical for similar indoor station apparatus. The flashover at 0.50 *RAD* again is somewhat better than one-half the voltage at 1.00 *RAD*.

Figure 8 presents typical data for 24-inch, 12-inch, and 6-inch rod gaps. Some of these tests cover a range from 0.10 to 1.50 *RAD*. The variations are much as would be expected for rod gaps. For the most part the curves are straight lines. Tests at low *RAD* show long times to sparkover as noted for apparatus. Other unusual effects were observed; for instance, below 0.05 *RAD* the collapse of the voltage would be abrupt on some tests and in others slow.

Wood is used extensively in transmission and distribution and, lately, in substations. For this reason, it was decided tests should be made. New, seasoned-fir crossarms for a 69-kv line were cut in lengths suitable to enclose in the cylinder and four-foot sections tested. The data, given in Figure 9, substantiate further the fact that wood is quite variable on impulse. However, the curves show clearly that the impulse strength of wood suffers a reduction with *RAD*.

The peculiar behavior of wood is evidenced from these tests. Time to flashover or breakdown for wood is 2 to 3 microseconds at normal *RAD*. At 0.50 *RAD* critical flashover occurs at 12 to 15 microseconds, and this would indicate that air is a primary factor in the breakdown. When breakdown occurs in the air, the voltage collapses suddenly to zero. In some of the tests the collapse is slow, followed by a residual voltage which indicates a discharge in the wood somewhat in the manner of an arrester. These effects are indicated in oscillo-

Figure 5. Testing of wood crossarm

Cylinder provided with porthole window for viewing test

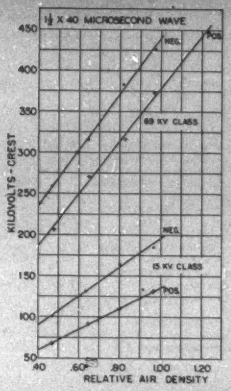

Figure 6. Critical-impulse flashover of standard switch and bus insulators

Atmospheric conditions
Temperature, 25 degrees centigrade
Barometer, 740 millimeters
Humidity, 16 millimeters

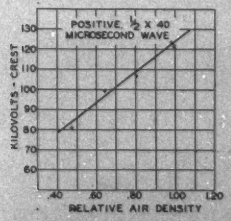

Figure 7. Critical-impulse flashover of 15-kv indoor dry-type current transformer

Atmospheric conditions
Temperature, 27 degrees centigrade
Barometer, 730 millimeters
Humidity, 12.5 millimeters

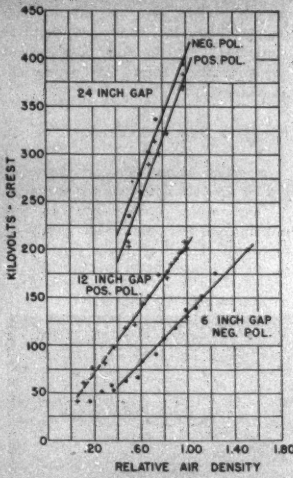

Figure 8. Critical-impulse sparkover of rod gaps

Atmospheric Conditions

Gap	Polarity	Barometer (Millimeters)	Temperature (Degrees Centigrade)	Humidity (Millimeters)
24	negative	730	25	17
24	positive	734	25	19
12	positive	747	20	8
6	negative	733	18	12

grams E of Figure 15. The streamers at the low *RAD*, often extending over a long section of the wood without completing the breakdown, were plainly visible. The splintering was moderate as the currents were limited to a few thousand amperes.

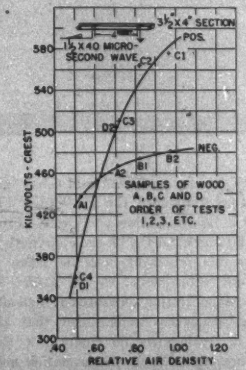
3½ X 4" SECTION
1½ X 40 MICRO-SECOND WAVE
POS.
NEG.
SAMPLES OF WOOD A, B, C AND D
ORDER OF TESTS 1, 2, 3, ETC.
KILOVOLTS - CREST
RELATIVE AIR DENSITY

Figure 9. Critical-impulse flashover of four-foot fir crossarm

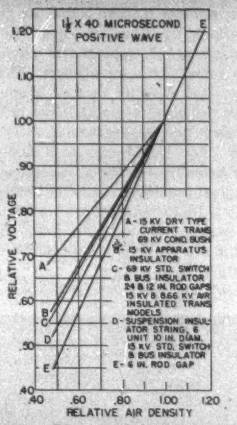
1½ X 40 MICROSECOND POSITIVE WAVE
A - 15 KV DRY TYPE CURRENT TRANS
69 KV COND. BUSH
B - 15 KV APPARATUS INSULATOR
C - 69 KV STD. SWITCH & BUS INSULATOR 24 & 12 IN. ROD GAPS 15 KV & 8.66 KV AIR INSULATED TRANS MODELS
D - SUSPENSION INSULATOR STRING, 6 UNIT 10 IN. DIAM. 15 KV STD. SWITCH & BUS INSULATOR
E - 6 IN. ROD GAP
RELATIVE VOLTAGE
RELATIVE AIR DENSITY

Figure 10. Effect of air density on critical-impulse flashover and sparkover

At the high *RAD* all tests were accompanied by vigorous noise upon flashover or sparkover. At 0.50 *RAD* the noise would dwindle materially and practically vanish at very low densities.

Beside testing typical apparatus, tests were made on insulation of interest in engineering. In Figures 10 and 11, these and the previous data are plotted in the convenient form of correction factors. For the apparatus in air the curves cluster close to a line that runs from unity through zero. A conservative procedure would be to consider the impulse level of station and line apparatus in air as directly proportional to the *RAD* after it is recognized that the positive impulse generally determines the

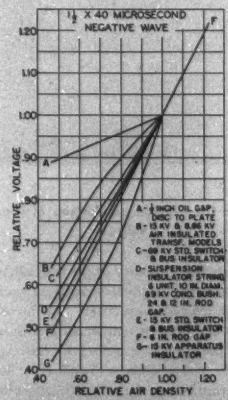
1½ X 40 MICROSECOND NEGATIVE WAVE
A - 4 INCH OIL GAP, DISC TO PLATE
B - 15 KV & 8.66 KV AIR INSULATED TRANSF. MODELS
C - 69 KV STD. SWITCH & BUS INSULATOR
D - SUSPENSION INSULATOR STRING, 6 UNIT, 10 IN. DIAM. 69 KV COND. BUSH. 24 & 12 IN. ROD GAP
E - 15 KV STD. SWITCH & BUS INSULATOR
F - 6 IN. ROD GAP
G - 15 KV APPARATUS INSULATOR
RELATIVE VOLTAGE
RELATIVE AIR DENSITY

Figure 11. Effect of air density on critical-impulse flashover and sparkover

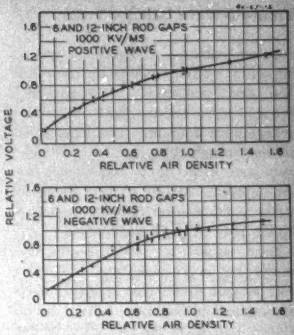

Figure 12. Front-of-wave sparkover of rod gaps

Points are typical of the spread and represen values for 12-inch rod gap
Atmospheric conditions
Temperature, 22 degrees centigrade
Barometer, 742 millimeters
Humidity, 9.0 millimeters

level. For a most exact evaluation of the correction factors reference should be made to Figures 10 and 11.

Curve *A* of Figure 11 shows a reduction of ten per cent in the strength of oil from 1.00 to 0.50 *RAD*. This is not a major reduction considering that the corresponding altitude is from sea level to practically 20,000 feet. Solid insulation impregnated in oil is probably affected even less. For this reason, station and line apparatus immersed in insulating liquid can be considered as little affected by altitude. At the very high altitudes the strength of solid and liquid insulation may have to be examined, particularly, if for any reason the low air density affects the condition of the insulation.

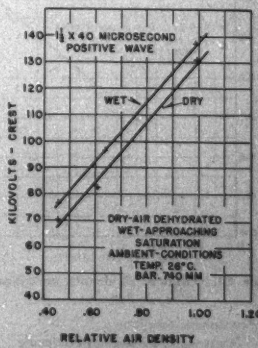

Figure 13. Effect of humidity on critical-impulse sparkover of six-inch rod gap

Front-of-Wave Impulse Tests

Direct strokes of lightning are an important consideration in the co-ordination and protection of apparatus.[23] Front-of-wave impulse data at low air densities are desirable, since lightning is present at high altitudes.[24] Accordingly, tests were made on 6- and 12-inch rod gaps, and the data are given in Figure 12 in the form of correction factors. F of Figure 15 is a typical oscillogram.

From normal to 0.50 *RAD* the correction on an average basis is 0.5 per cent per 0.01 *RAD;* that is, at 0.75 *RAD* the correction factor is 0.87. Within 0.90 to 1.10 *RAD* the correction is less, 0.35 per cent per 0.01 *RAD*. Within this limited *RAD* range a similar correction for short impulses has previously been reported.[25] For practical purposes the curves in Figure 12 can be considered applicable to high-voltage apparatus which have essentially a rod-gap type of characteristic.

Humidity and Other Effects

Comparative tests were made on the six-inch rod gap to determine the effect of humidity at low air densities. First, the tests were made in dry air, supplied from a calcium-chloride–phosphorous-pentoxide desiccator. The tests were repeated in a humid atmosphere produced by a pan of water in combination with cloth wicks introduced into the test cylinder. All tests were with a $1^1/_2 \times 40$-microsecond positive wave. The results are plotted in Figure 13.

The same vapor pressure maintains for normal and low air pressures.[26] We estimate the humidified air attained 0.80-inch mercury vapor pressure or better. From the two curves we note a constant difference of eight kilovolts throughout. It appears that physically the humidity has a fixed effect. Thus on a per cent basis the increase in strength from dry air to 0.80-inch vapor pressure is nearly twice as great at 0.50 *RAD* as at 1.00 *RAD*. On the strength of these data the humidity corrections determined at sea-level conditions cannot be applied at high altitudes but require a scaling up in an inverse relation to the *RAD*. Additional tests are desirable to establish these relations fully.

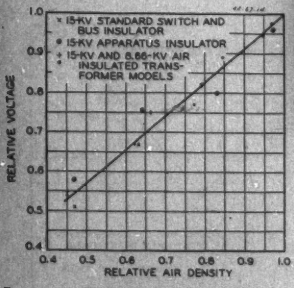

Figure 14. Effect of air density on critical 60-cycle flashover

Atmospheric conditions
Temperature, 29 degrees centigrade
Barometer, 735 millimeters
Humidity, 18.3 millimeters

rays, ultraviolet rays, and similar ionizing agents upon the strength of electrical apparatus. At the high altitudes in particular these effects may require examination.

60-Cycle Data and Corona

As stated before, 60-cycle studies at low air densities date from the beginning of high-voltage transmission. In this investigation tests were made mostly on apparatus typical of indoor type. The results are given in Figure 14. Breakdown data for a uniform field where temperature controlled the *RAD* from 1.00 to 0.50 likewise follow this curve. From all data at hand the 60-cycle strength of apparatus practically can be taken as directly proportional to the *RAD*. In applying or testing apparatus at high altitudes it seems fundamental that the voltage ratings should conform to this relationship. Where the insulation margins are inherently large and there are no other limitations, as is the case for

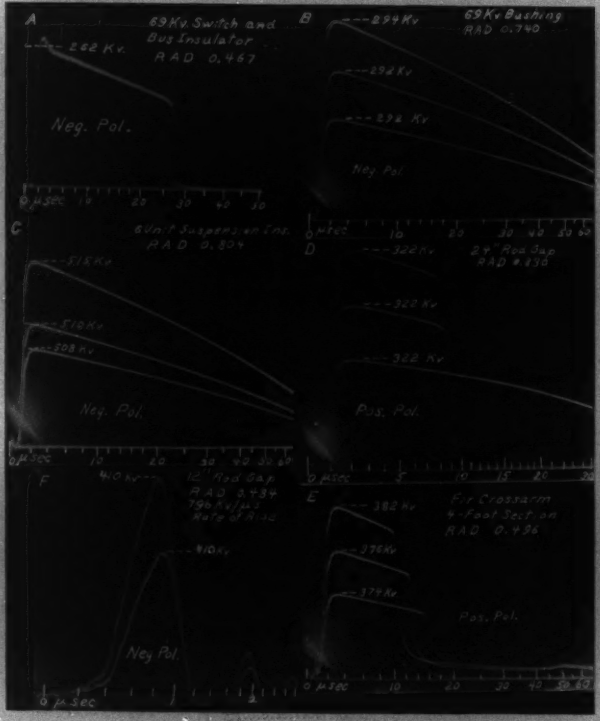

Figure 15. Typical oscillograms of impulse voltages

However, humidity drops with altitude so that actual conditions mitigate against a large over-all correction. On the other hand, the drop in temperature with altitude improves the strength, but again the effect is secondary (Table II). Aside from rain, snow, and so forth, there may be other factors; for instance, little apparently is known of the effect of cosmic

some of the low-voltage equipment, no derating appears necessary other than possibly at the very high altitudes.

We had planned to investigate corona at low air densities, particularly its effect on insulation and radio noise, but other activities have deferred these tests. For instance, there is the possibility that apparatus may operate at high altitude with more apparent corona than would be permissible at sea level. The dry atmosphere at high altitude may also contribute beneficially to longer insulation life. The question of corona losses on lines is of particular interest to transmission engineers, and this also may require further examining in the light of the actual conditions prevailing at the high altitudes. These are some of the corona effects on which more study and testing may be well worth while.

Summary

The air strength of electrical apparatus to long waves ($1^1/_2$x40 microseconds) is essentially proportional to the *RAD*. The impulse strength of apparatus applied at high altitudes and exposed to lightning should be rated accordingly.

The *RAD* corrections for front-of-wave impulses (1,000 kv/microsecond) are one half and less than one half of those for long waves.

Sixty-cycle strength and corona are also affected in direct relation to the *RAD*. Voltage ratings naturally should recognize this.

The oil strength of apparatus is practically unaffected by altitude.

Data on the effect of humidity are presented. Other influencing factors that may be present at high altitude are discussed. Corona effects may need more attention.

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A 500,000-Kva 7.5-Kv Air Circuit Breaker for Steel-Mill Service

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Synopsis: A self-contained air circuit breaker for a rating of 500,000 kva at 7.5 kv has long been regarded as a desirable goal. Recent developments in magnetic-type air circuit breakers have indicated the economic feasibility of similar designs for ratings higher than previously attained. The development of a 500,000-kva 7,500-volt magnetic air circuit breaker is described. A description of the breaker and the peculiar design problems are presented. Test data with oscillograms are shown.

WITH the advent of the first 15-kv power air circuit breakers for central station service in 1929,[1,2] it was soon

Figure 1. 7.5-kv 250,000-kva deion air circuit breaker for metal-clad switching equipment as widely applied in steel-mill service

recognized that an air circuit breaker was much more desirable for highly repetitive steel-mill motor switching than was the conventional equipment universally used at that time. Interrupting tests showed that the air circuit breaker could withstand many operations on considerable power without requiring maintenance, as compared to the high maintenance necessary on oil switching equipment of that period. This was somewhat to be expected in view of the fact that low-voltage air circuit breakers and contactors had demonstrated this ability for years. It was also believed that the air circuit breaker was highly desirable for steel-mill-substation service because of the additional severity of steel-mill operating conditions, as compared to the duty on corresponding equipment in central-station service.

Figure 2. Five-kilovolt 150,000-kva magnetic deion air circuit breaker

Realizing these facts, a 250,000-kva 7.5-kv deion air circuit breaker of the metal-plate type was made available in 1932, designed to meet the rigorous demands of steel-mill switching service, for either substation or motor switching duty. Illustrated in Figure 1, this breaker has been widely and successfully applied in some of the largest steel mills in the industry and continues to be applied in substantially its original form. The first breakers of this type, installed on large reversing mill motors in 1932, are still doing duty at the rate of about 50,000 operations per year.

The success of these breakers and of the companion designs for 2.5-, 5-, and 15-kv ratings has been largely responsible for a general trend toward air circuit breakers in this range. However, the problem of interrupting higher currents at higher kilovolt-ampere ratings disclosed economic limitations in the metal plate deion principle indicating limits in current interrupting rating beyond which construction would be too expensive for general use. Thus, the ratings of 250,000 kva at five kilovolts and 500,000 kva at 7.5 kv, involving currents of 30,000 to 45,000 amperes, were considered beyond the range of economic use of the metal plate deion principle. The development of a new principle of arc interruption in air[3,4] made possible the attainment of higher short-circuit current interrupting ability at 2,500 volts than was practical with previous designs. This new principle made use of magnetic diffusion effects with plates of refractory insulating materials.

Through considerable experimental work and study of this principle, five-

Figure 3. Five-kilovolt 250,000-kva magnetic deion air circuit breaker

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kilovolt breakers of 150,000-kva and 250,000-kva interrupting ratings were developed[3] as illustrated in Figures 2 and 3. The short-circuit current which must be interrupted by the 250,000-kva five-kilovolt breaker is 35,000 amperes at the commonly encountered distribution voltage of 4,150. Figure 4 is an oscillogram showing the interrupting by this breaker of 40,000 amperes at 4,020 volts restored, on a single pole, which shows considerable margin for a three-phase rating of 250,000 kva in the five-kilovolt class. This development contributed greatly to the technique of interrupting high currents at higher voltages than previously deemed feasible for a self-contained air circuit breaker.

However, a 500,000-kva breaker for 7.5 kv still remained to complete the

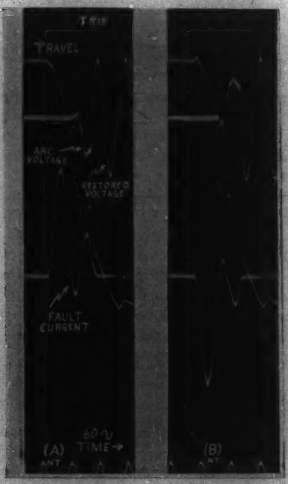

Figure 4. Oscillogram showing interruption of 40,000 amperes at 4,020 volts restored on a single pole of a five-kilovolt 250,000-kva magnetic deion air circuit breaker

Equivalent three-phase kilovolt-amperes—330,000 kva

line of self-contained air circuit breakers. The breaker herein described completes the need previously indicated.

The general requirements which should be set by a breaker of this rating are:

1. Interrupting capacity of 44,000 amperes at 6,600 volts, three phase.
2. Full interrupting rating at 25 cycles as well as 60 cycles which is often required.
3. General ruggedness and freedom from excessive maintenance requirements.
4. Insulation level adequate for the new insulation standards of 95-kv impulse strength and 36-kv one-minute 60-cycle test.
5. Readily suited to use in the compacted space of metal-clad switching equipment.

The problem of interrupting heavy-current arcs in a restricted space in air is more difficult at the higher currents and especially at the higher voltages. Twenty thousand amperes does not now present a very serious problem, but 40,000 amperes presents much more than double the 20,000-ampere job. The interrupting of 44,000 amperes at 7.5 kv presents problems in arc control and space de-

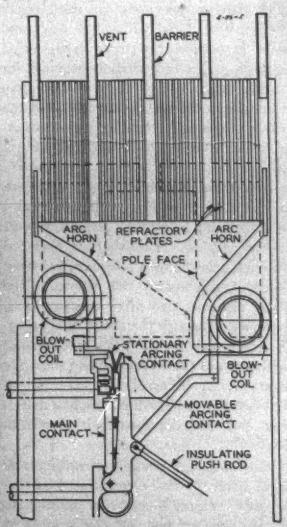

Figure 5. Schematic illustration of construction of 500,000-kva 7.5-kv magnetic deion air breaker

ionization far beyond those dealing with more moderate currents.

The initial drawing of the arc on the arc tips, even with the best materials available, gives rise to large quantities of ionized gas which must be disposed of if the space between the contacts and other live parts in the arc chamber is to withstand the restored voltage of the circuit. From its inception the arc space must be conditioned progressively to withstand the increasing voltages imposed by the action of the interrupter on the arc. If the arc in moving from the contacts into the interrupter is envisioned in slow motion—keeping in mind the intense heat and ionization—it can be seen that at each point, the space which the arc

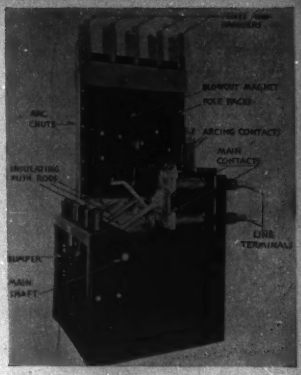

Figure 6. Three-pole 500,000-kva 7.5-kv magnetic deion air breaker showing one arc chute in position

has just vacated must be sufficiently deionized to withstand the voltage of the arc in the succeeding position. Otherwise, the arc will restrike to the earlier position, from which it must again be moved. Although it is difficult to avoid this restriking with perfection, excessive restriking causes proportionally greater ionization which must be disposed of for successful interruption of the circuit. Finally, the entire space between the live parts of the arc chamber, both internal and external, must withstand the restored voltage applied by the open circuit.

The interrupting element or arc chute of this breaker is arranged so that the arc is moved by a magnetic field into V-shaped slots in a multiplicity of refractory plates separated from each other. The planes of the plates are perpendicular to the arc stream. The arc chute is shown schematically in Figure 5. The lower part encloses the initial arc-drawing space and the space for extending the arc length for movement into the series of refractory deionizing plates.

A curved arc horn is located at each end of this lower part of the arc chute to provide rapidly separating arc terminal paths. Each arc horn is on the immediate upper periphery of a circular blowout coil. The coil above the stationary arcing contact is cut into series relationship with the arc as the arc impinges on the arc horn immediately above that coil. This adds sufficient magnetic field to that existing from the loop shape of the current path through the breaker to move the terminal of the arc on the movable arc tip rapidly onto the arc horn at the other end of the arc

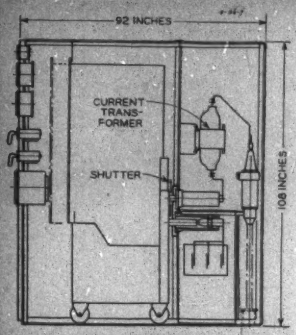

Figure 7. Dimensioned drawing showing 500,000-kva 7.5-kv magnetic deion air breaker in metal-clad switching equipment

Type 75–DH–500 drawout unit 40 inches wide

chute and the corresponding blowout coil is introduced into the circuit. The magnetic field provided by the two blowout coils is applied to the arc space by suitably shaped pole faces, to move the arc as uniformly and as rapidly as possible consistent with the deionization of all of the space behind it. The deionization of this space between the contacts and arc horns is accomplished by venting the gases from the arc and cooling them to such an extent that breakdown will not occur. To this end the arc horns are vented freely, and the refractory plates above the arc horns are arranged in four groups spaced apart to provide five relatively wide vents evenly spaced.

The refractory plates are separated as much as possible for venting effect without sacrificing the deionization effect on the exhaust gases traveling from the ends of the V-shape slots to the ends of the plates. Lateral barriers are also placed at the end stack vent as an additional precaution against flashing over the entire end of the arc chamber.

In Figure 5, the arcing contacts are externally similar to those previously applied to magnetic deion breakers for 100,000, 150,000, and 250,000 kva[3–5] but are equipped with heavier springs to prevent blowing open on the high currents involved. The arc tips and secondary contacts are made of silver tungsten. The main contacts are of the solid copper bridge type, faced with silver inlay and held in contact by strong compression springs. This construction provides for transferring the current from the main contacts to the arcing contacts, and the shape of the arcing contact parts accelerates the movement of the arc from the arc tips.

The three movable contact arms are operated by insulating push rods from a shaft running lengthwise across the front of the breaker. This shaft is operated through a toggle by a horizontally acting solenoid mechanism not shown. The shaft also has two arms coacting with bumpers to absorb the shock of opening.

Figure 6 shows the three-pole breaker with two arc chutes removed to show the contacts. A dimensional drawing of this breaker as part of a complete metal-clad switching equipment is shown in Figure 7.

Extensive high-power interrupting tests were made in the development of the breaker. Figure 8 shows an oscillogram of an opening test on the completed breaker of 47,500 amperes at 5,900 volts, 60 cycles on a single pole. Figure 9 shows a close–open test of 45,700 amperes at 6,100 volts, 25 cycles on a single pole.

Table I. Single-Phase Interrupting Tests

7,500-Volt 500,000-Kva Steel-Mill Circuit Breaker

Test Number	Generator Voltage	Rms Amperes Interrupted	Arcing Time (Cycles)	Interrupting Time (Cycles)
Opening Tests 60 Cycles				
1	3,500	11,000	1.50	2.75
2	5,900	11,900	1.20	2.60
3	5,950	21,400	1.00	2.40
4	5,900	34,800	1.00	2.40
5	3,500	11,400	1.00	2.50
6	5,900	30,500	0.80	2.30
7	5,900	29,200	0.90	2.30
8	5,900	21,000	0.80	2.20
9	5,900	46,550	0.80	2.20
10	5,900	47,250	1.10	2.60
11	5,900	47,250	0.75	2.30
12	5,900	46,950	1.25	2.60
Opening Tests 25 Cycles				
13	5,850	5,225	0.50	1.00
14	5,850	21,850	0.45	0.90
15	3,500	20,250	0.45	0.95
16	6,100	29,200	0.40	1.20
17	6,100	43,700	0.50	1.00
18	6,150	42,800	0.40	0.90
Close–Open Tests 25 Cycles				
19	6,100	1,415	1.20	1.70
20	6,100	42,900	0.40	0.90
21	6,100	45,700	0.60	1.20

Table I shows three series of tests on a single pole of the breaker, all of which were made without maintenance. Of the 21 tests, 8 are at more than 40,000 amperes and 16 are at more than 20,000 amperes. This performance is equivalent to years of actual service. Proof of satisfactory performance over the entire range of lower currents was obtained by subjecting the breaker, without any form of maintenance, to a series of approximately 100 interrupting tests.

Conclusion

The principle of magnetic diffusion has been applied to a complete line of circuit breakers with interrupting capacities

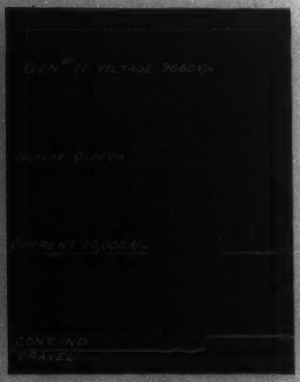

Figure 8. Oscillogram showing the interruption of 47,500 amperes at 5,900 volts at 60 cycles on a single pole of the 500,000-kva 7.5-kv magnetic deion air breaker

Figure 9. Oscillogram similar to Figure 9 except showing a single-phase close–open interruption of 45,700 amperes with a generator voltage of 6,100 and at 25 cycles

The Asymmetrical Stator as a Means of Starting Single-Phase Induction Motors

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THE shaded-pole motor is quite simple to construct; but for all but the smallest sizes, losses are large; and if distributed windings are used, its construction becomes more complicated. A single-phase induction motor may be given starting torque by varying the rotor constants over the pole face, either by asymmetrical iron structure or winding. Starting torque is comparable with that of a shaded-pole motor, and construction is very simple with nothing to get out of order. The chief drawback appears to be the smaller power factor which is due to reduced mutual inductance.

Means of Securing an Asymmetrical Stator

Starting torque arises from two sources:

1. The difference in leakage inductance of the rotor bars on one side of the pole from that on the other causes a different current to flow on each side, producing a resultant torque, as in a repulsion motor.

2. The difference in mutual reactance on the two sides of the poles gives the rotor current under the two sides some difference in phase, which also produces a resultant torque.

One means of securing these differences is to wind more turns about one side of the pole face, which we will designate as *a*, than about the other side, designated *b*, thus causing a difference in the permeability of both the rotor and stator iron. If the iron at *b* has the maximum permeability, the flux density at *a* will be above that of maximum permeability; the rotor bars under *b* will have greater inductance than those under *a*, and since the current through these encircles *a*, the component of rotor leakage reactance X_{2a} will be greater than X_{2b}. For a lower voltage and flux density, the opposite will be the case; hence, we have the interesting possibility of the starting direction being reversed by a change in starting voltage. In order to utilize this effect fully, the rotor bars should be surrounded completely by iron. It is quite difficult to calculate the rotor reactance of this type of motor; thus, it is hard to design efficiently.

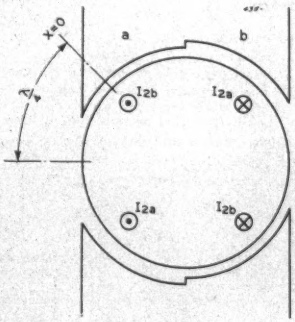

Figure 1. Relative position of fluxes and currents

The case of varying the air gap over the pole face is easier to calculate. These formulas are derived in the appendix. While the greatest difference in both rotor inductance and mutual reactance occurs when the air gap has its maximum value over half the pole face, changing abruptly to a minimum, harmonic reactances of the rotor are least when the so-called zigzag reactance, that is, leakage reactance of the rotor bars due to flux crossing the air gap, varies sinusoidally over each pole. If it is assumed that this reactance is to be inversely proportional to the air gap, this requires that

$$1/\Delta = {}_0A + {}_2A \cos 2\pi x/\lambda \qquad (1)$$

where

Δ = air gap (all dimensions in this paper are given in inches)
${}_0A = (1/2)(1/\Delta_{min} + 1/\Delta_{max})$
${}_2A = (1/2)(1/\Delta_{min} - 1/\Delta_{max})$
x = co-ordinate measured along rotor periphery
λ = pole pitch

It might seem desirable to create a sinusoidal flux wave by increasing the turns about each stator tooth in proportion to the increase in air gap under that tooth. This introduces harmonics into the magnetomotive-force wave which gives a greater harmonic content to the mutual reactance than an ordinary sinusoidally distributed winding would give.

Difference in flux density over *a* and *b* may cause difference in rotor permeability, which may increase or decrease the resultant torque; but unless the rotor bars are surrounded completely by iron, this effect should be small. Difference in flux density over *a* and *b* also may produce a difference in hysteretic angle of advance between flux *a* and *b*, producing a rotating field; but this effect is also quite small under ordinary conditions.

Computation of Rotor Currents and Torque

P. H. Trickey[1] has given an analysis of the shaded-pole motor which forms the basis of this development. The space distribution waves of field flux and rotor current are resolved into Fourier series. Each harmonic is divided into two components or phases 90 degrees apart, denoted by subscripts *a* and *b*. In Appendix II the values of these components are calculated. Figure 1 shows the relative position of the fields and currents for the

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ranging from 50,000 kva[4] at 2,500 volts to the 500,000-kva 7.5-kv breaker described in this paper. Laboratory tests show that this most recent breaker is well suited to the operating conditions of steel mill and equivalent service and that it has ample short-circuit interrupting capacity for use in large power concentrations at 6,600 or 6,900 volts.

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fundamental flux wave; Figure 2 shows the equivalent circuit diagram. If we add voltages about the shunt circuits a and b associated with the nth harmonic, we get

$$({}_nR_{2a}+j\,{}_nX_{2a})\,{}_nI_{2a}=(I-{}_nI_{2a})j\,{}_nX_a+nS(I-{}_nI_{2b})\,{}_nX_b-nS\,{}_nI_{2b}\,{}_nX_{2b} \quad (2)$$

$$({}_nR_{2b}+j\,{}_nX_{2b})\,{}_nI_{2b}=(I-{}_nI_{2b})j\,{}_nX_b-nS(I-{}_nI_{2a})\,{}_nX_a+nS\,{}_nI_{2a}\,{}_nX_{2a} \quad (3)$$

where

${}_nR_{2a}$ = rotor resistance to nth space harmonic of current, phase a

(All impedances mentioned in body of paper are referred to primary.)

${}_nX_{2a}$ = rotor leakage reactance, nth harmonic, phase a

${}_nX_a$ = mutual reactance, nth harmonic, phase a

${}_nI_{2a}$ = rotor current, nth harmonic, phase a

(Similar quantities of phase b have subscript b.)

n = order of harmonic

S = ratio of rotor speed to synchronous speed, positive in direction of increasing x

Ordinarily the fundamental flux, $n=1$, is all that need be considered; but with a salient pole the third harmonic is apt to affect the torque appreciably. The equivalent resistance, R_h, due to iron loss, should be included as shown, but its computation is outside the province of this paper, its chief effect being to increase the inphase component of current.

If equations 2 and 3 are solved simultaneously for ${}_nI_{2a}$ and ${}_nI_{2b}$

$${}_nI_{2a}={}_nK_a I \qquad {}_nI_{2b}={}_nK_b I \quad (4)$$

$${}_nK_a={}_nF_a/{}_nF \qquad {}_nK_b={}_nF_b/{}_nF \quad (5)$$

$${}_nF_a=nS\,{}_nR_{2b}\,{}_nX_b-(1-n^2S^2){}_nX_{ab}\,{}_nX_a+j\,{}_nR_{2b}\,{}_nX_a \quad (6)$$

$${}_nF_b=-nS\,{}_nR_{2a}\,{}_nX_a-(1-n^2S^2){}_nX_{ab}\,{}_nX_b+j\,{}_nR_{2a}\,{}_nX_b \quad (7)$$

$${}_nF={}_nR_{2a}\,{}_nR_{2b}-(1-n^2S^2){}_nX_{ab}\,{}_nX_{ab}+j({}_nR_{2a}\,{}_nX_{ab}+{}_nR_{2b}\,{}_nX_{ab}) \quad (8)$$

where

${}_nX_{ab}={}_nX_a+{}_nX_b$ and so forth.

In the primary circuit

$$I(R_1+jX_1)+(I-{}_1I_{2a})j\,{}_1X_a+(I-{}_1I_{2b})j\,{}_1X_b+(I-{}_1I_{2a})j\,{}_1X_a+(I-{}_1I_{2b})j\,{}_1X_b=E$$

where

R_1 = primary resistance

X_1 = total primary leakage reactance, excluding ${}_1X_a$ and ${}_1X_b$

E = voltage

If the values of ${}_1I_{2a}$ and so forth are put in from equation 4

$$I[R_1+j(X_1+X_1')-{}_1K_a j\,{}_1X_a-{}_1K_b j\,{}_1X_b-{}_1K_a j\,{}_1X_a-{}_1K_b j\,{}_1X_b]=E \quad (9)$$

where

X_1 = total mutual reactance

X_1' = primary leakage reactance, excluding harmonic and skew reactance

Torque in ounce inches for the nth harmonic is given by the real part of

$${}_nT=11.3(nP/f)[({}_nt_b/{}_nt_a){}_nX_a(I-{}_nI_{2a})\times \text{conj}\ {}_nI_{2b}-({}_nt_a/{}_nt_b){}_nX_b(I-{}_nI_{2b})\times \text{conj}\ {}_nI_{2a}] \quad (10)$$

where

P = number of poles

f = frequency

${}_nt_a$ = turns per pole effective for nth harmonic, phase a

Let us put this formula into a form more suitable for computation. Now ${}_nK_a$ and ${}_nK_b$ are complex, and so we may put them in the form

$${}_nK_a={}_nU+j\,{}_nu \qquad {}_nK_b={}_nV+j\,{}_nv$$

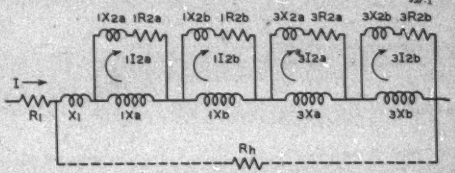

Figure 2. Equivalent circuit diagram of asymmetrical field induction motor

If we substitute these expressions in equation 4, we find that the real part of

$$(I-{}_nI_{2a})\ \text{conj}\ {}_nI_{2b}=I^2(1-{}_nU-j\,{}_nu)({}_nV-j\,{}_nv)=I^2[{}_nV-({}_nU\,{}_nV+{}_nu\,{}_nv)]$$

$$(I-{}_nI_{2b})\,\text{conj}\,{}_nI_{2a}=I^2(1-{}_nV-j\,{}_nv)\times({}_nU-j\,{}_nu)=I^2[{}_nU-({}_nU\,{}_nV+{}_nu\,{}_nv)]$$

so that

$${}_nT=11.3({}_nPI^2/f)[({}_nt_b/{}_nt_a){}_nX_a[{}_nV-({}_nU\,{}_nV+{}_nu\,{}_nv)]-({}_nt_a/{}_nt_b){}_nX_b[{}_nU-({}_nU\,{}_nV+{}_nu\,{}_nv)]] \quad (11)$$

Standstill Conditions

When $S=0$, the system of equations 4 to 8 reduces to

$${}_nK_a=j\,{}_nX_a/({}_nR_{2a}+j\,{}_nX_{ab})=({}_nK_{ra}/{}_nX_a)({}_nX_{ab}+j\,{}_nR_{2a}) \quad (12)$$

where

${}_nK_{ra}=({}_nX_a/{}_nX_{ab})^2/[1+({}_nR_{2a}/{}_nX_{ab})^2]$

with a similar formula for b.

When $t_a=t_b$ and $R_{2a}=R_{2b}=R_2/2$ (R_2 being the complete fundamental rotor resistance as calculated by usual methods), as is often the case, equation 12 becomes, for $n=1$

$${}_1T=11.3(P\,{}_1K_{ra}\,{}_1K_{rb}/{}_1X_a\,{}_1X_b f)I^2\times[({}_1X_{2b}-{}_1X_{2a})({}_1R_2{}^2-{}_1X_{ab}\,{}_1X_{ab})-2\,{}_1R_2{}^2({}_1X_a-{}_1X_b)] \quad (13)$$

showing that the torque depends on both ${}_1X_{2b}-{}_1X_{2a}$ and ${}_1X_a-{}_1X_b$. Since we may put ${}_1R_{2a}=R_2'{}_1t_a{}^2$ and ${}_1X_{2a}=X_{2a}'{}_1t_a{}^2$, and so forth, it becomes evident on putting these values in equation 11 for $S=0$, that starting torque is independent of any difference in t_a and t_b, except as they affect the permeability.

Motor Constants With Sinusoidal Permeance

With an ordinary symmetrical winding, $t_a=t_b=t_p/\sqrt{2}$ and $R_{2a}=R_{2b}=R_2/2$, where t_p is the effective turns per pole calculated in the usual manner.

With the air gap of equation 1, and with any type of winding

$$R_{2a}=8(Pt_a)^2\left[\left(\sqrt{W^2+Sk^2}/S_cS_c\right)+\frac{\rho}{(0.637D_rK_r/S_rP^2)}\right] \quad (14)$$

where

P = number of rotor slots

S_c = cross section of rotor bar

Sk = skew in inches

S_r = cross section of end ring

W = axial width of rotor

ρ = resistivity

D_r = diameter of end ring

K_r = ring constant (see reference 2)

For R_{2b} use t_b instead of t_a

$$X_{2a}=X_{sa}+X_{ska}+(X_{2a\ max}+X_{2a\ min})/2-(X_{2a\ max}-X_{2a\ min})/4 \quad (15)$$

$$X_{2b}=X_{sb}+X_{skb}+(X_{2b\ max}+X_{2b\ min})/2+(X_{2b\ max}-X_{2b\ min})/4 \quad (16)$$

X_{sa} = rotor slot reactance, phase a
$= 2\pi f(Pt_a)^2\ 10^{-9}25.52\,(WK_s/S_s)$ (17)

K_s = rotor slot constant (see reference 1)

For X_{2b} use t_b

$$X_{2a\ max}=2\pi f(Pt_a)^2 10^{-9}25.52(WT_f/S_s4\,\Delta_{min}) \quad (18)$$

T_f = rotor tooth face in inches

For $X_{a\,min}$ use Δ_{max}, for $X_{b\,min}$ use l_b and Δ_{max}, and so forth. The preceding formula applies only when there are no stator slots to break the magnetic circuit, and when the rotor bars are not completely surrounded by iron

$$X_{a2c}=(1-C_{sk})X_a' \qquad X_{2b}=(1-C_{sk})X_b' \tag{19}$$

$$C_{sk}=\sin(\pi Sk/2\lambda)/(\pi Sk/2\lambda) \tag{20}$$

Since $\sin x=x-x^3/6$ for small values of x

$$1-C_{sk}=(1/6)(\pi Sk/2\lambda)^2 \tag{21}$$

approximately for small values of Sk/λ.

Thus

$$X_{2b}-X_{2a}=(X_{z\,max}-X_{z\,min})/2-(X_a-X_b)(1-C_{sk}) \tag{22}$$

If equation 22 is substituted in equation 13, the term in brackets becomes

$$(R_s^2-X_{ac}X_{ab})(X_{z\,max}-X_{z\,min})/2-(X_a-X_b)[(R_s^2-X_{ac}X_{ab})(1-C_{sk})+2R_s^2] \tag{23}$$

Thus the effect of zigzag reactance is opposed to that of skew. When R_s is small, it may be desirable to reduce X_{ac} and X_{ab} as much as possible, depending on $X_{a2c}-X_{a2b}$ for starting torque by increasing the skew an integral number of slots. When $2R_s$ is greater than $(R_s^2-X_{ac}X_{ab})(1-C_{sk})$, it may be desirable to reduce the skew as much as possible. Since, in all practical cases, R_s^2 is less than $X_{ac}X_{ab}$, torque from zigzag reactance in this case is in the same direction as that due X_a-X_b. The increase of R_s increases the torque per ampere (until it approaches the magnitude of X_{ab}), though it reduces the current; however, increase of R_s increases the slip and losses and decreases the power factor, as in any induction motor. Since X_a-X_b and $X_{2b}-X_{2a}$ usually must be increased by reducing X_b, the starting torque is limited by the decrease in power factor and increase in rotor losses permissible.

Appendix I. Equivalent Impedance of Squirrel-Cage Rotor

Let there be an infinite number of rotor bars having the same impedance for an inch of periphery as the actual rotor. Figure 3 represents an elementary circuit about the rotor. AB and DC are the endrings, AD being the bar where the ring current $I_r=0$. Then at x

$$I_r=\int_c^x J\,dx$$

where J = current density in bars per inch of periphery.

The voltage drop E_r in each ring from x to d is

$$E_r=R_r\int_x^d I_r\,dx=R_r\int_x^d dx\int_c^x J\,dx$$

where R_r = resistance per inch of end ring.

Let the voltage induced at x be $E(x)$ and that, at a fixed point, d be $E(d)$. Then the voltage about the whole circuit is

$$Jdx(Z_1/dx)+2R_r\int_x^d dx\int_c^x J\,dx=E(x)-E(d) \tag{24}$$

where

$Z_1=Z_{2b}\lambda P/S_s$ = impedance of one inch of bars at x

Z_{2b} = actual impedance of one bar (25)

If we differentiate twice, and remember that $E(d)$ is constant

$$(d^3/dx^3)(JZ_1)+2R_rJ=d^2E/dx^2 \tag{26}$$

We may represent J, E, and Z_1 in a Fourier series in which

$\theta=\pi x/\lambda$

$$J={}_1J_a\sin\theta+{}_2J_a\sin 3\theta+\ldots+{}_1J_b\cos\theta+{}_2J_b\cos 3\theta+\ldots \tag{27}$$

$$E={}_1E_a\sin\theta+{}_2E_a\sin 3\theta+\ldots+{}_1E_b\cos\theta+{}_2E_b\cos 3\theta+\ldots \tag{28}$$

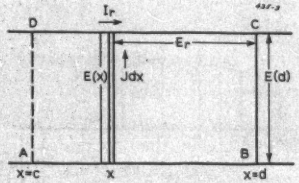

Figure 3. Rotor circuit diagram

$$Z_1={}_0C+{}_2C\sin 2\theta+{}_4C\sin 4\theta+\ldots+{}_0D+{}_2D\cos 2\theta+\ldots \tag{29}$$

Z_1 has a period of 2θ because it repeats at every pole. In order to solve the differential equation 26, it is necessary only to substitute in it equations 27, 28, and 29. Now, if we put equations 27 and 29 in more concise form

$$JZ_1=\left(\sum_q {}_qJ_a\sin q\theta+\sum_q {}_qJ_b\cos q\theta\right)\times\left(\sum_p {}_pC\sin p\theta+\sum_p {}_pD\cos p\theta\right) \tag{30}$$

If we use product formulas of the type

$$\sin m\theta\sin n\theta=-(1/2)\cos(m+n)\theta+(1/2)\cos(m-n)\theta$$

we find, by expanding equation 30

$$JZ_1=(1/2)\sum_p\sum_q {}_pC\,{}_qJ_a[-\cos(p+q)\theta+\cos(p-q)\theta]+(1/2)\sum_p\sum_q {}_pC_qJ_b[\sin(p+q)\theta+\sin(p-q)\theta]+(1/2)\sum_p\sum_q {}_pD_qJ_a\times[\sin(p+q)\theta-\sin(p-q)\theta]+(1/2)\sum_p\sum_q {}_pD_qJ_b[\cos(p+q)\theta+\cos(p-q)\theta] \tag{31}$$

where the summation extends over all the positive values of p and q for which D and C exist. Pick out the coefficient of $\sin n\theta$ in ${}_pC_qJ_b\sin(p+q)\theta$, where $n=p+q$; it is

$$\sum_q {}_{n-q}D\,{}_qJ_b$$

Likewise, in the term ${}_pC_qJ_b\sin(p-q)\theta$, the coefficient of $\sin n\theta$, where $n=p-q$, is

$$\sum_q {}_{n-q}C\,{}_qJ_b-\sum_q {}_{q-n}C\,{}_qJ_b$$

for when $q>p$, n is negative, and the terms are of the form

$${}_{q-|n|}C\,{}_qJ_b\sin(-|n|\theta)=-{}_{q-|n|}C\,{}_qJ_b\sin|n|\theta$$

where $|n|=q-p$. If we pick out the other coefficients in the same way

$$Z_1J=(1/2)\sum_n M_a\sin n\theta+(1/2)\sum_n M_b\cos n\theta \tag{32}$$

where

$${}_nM_a=\sum_q {}_{n-q}C\,{}_qJ_b-\sum_q {}_{q-n}C_{qa}J_b+\sum_q {}_{n+q}C\,{}_qJ_b+\sum_q {}_{n-q}D\,{}_qJ_a+\sum_q {}_{q-n}D\,{}_qJ_a-\sum_q {}_{n+q}D\,{}_qJ_a \tag{33}$$

$${}_nM_b=-\sum_q {}_{n-q}C\,{}_qJ_a+\sum_q {}_{q-n}C\,{}_qJ_a+\sum_q {}_{n+q}C\,{}_qJ_a+\sum_q {}_{n-q}D\,{}_qJ_b+\sum_q {}_{q-n}D\,{}_qJ_b+\sum_q {}_{n+q}D\,{}_qJ_b \tag{34}$$

As before, the summation extends over all positive values of q for which the factors C and D exist.

We are ready now to substitute the value of JZ_1, that is, equation 32, in equation 26

$$-\sum(n^2\pi^2/2\lambda^2)\,{}_nM_a\sin n\pi x/\lambda-\sum(n^2\pi^2/2\lambda^2)\,{}_nM_b\cos n\pi x/\lambda-2R_r\sum {}_nJ_a\sin n\pi x/\lambda-2R_r\sum {}_nJ_b\cos n\pi x/\lambda=-(\pi^3/\lambda^3)\left[\sum n^3\,{}_nE_a\sin n\pi x/\lambda-\sum n^3\,{}_nE_b\cos n\pi x/\lambda\right] \tag{35}$$

We may separate equation 35 in a different equation for each harmonic

$$[(1/2)\,{}_nM_a+2\lambda^2R_r\,{}_nJ_a/n^2\pi^2\sin(n\pi x/\lambda)]={}_nE_a\sin(n\pi x/\lambda) \tag{36}$$

$$[(1/2)\,{}_nM_b+2\lambda^2R_r\,{}_nJ_b/n^2\pi^2\cos(n\pi x/\lambda)]={}_nE_b\cos(n\pi x/\lambda) \tag{37}$$

Let us now confine our attention to the case in which all orders of C are zero. Then each value of ${}_nM_a$ is made up of terms including ${}_mJ_a$, and we get the system of equations in ${}_1J_a$ of the form

$$({}_{11}Z_a'\,{}_1J_a+{}_{12}Z_a'\,{}_2J_a+{}_{13}Z'_a\,{}_3J_a+\ldots)\times\sin\pi x/\lambda={}_1E_a\sin\pi x/\lambda$$

$$({}_{11}Z'_a\,{}_1J_a+{}_{22}Z_a'\,{}_2J_a+{}_{23}Z'_{1a}\,{}_3J_a+\ldots)\times\sin 3\pi x/\lambda={}_3E_a\sin 3\pi x/\lambda \tag{38}$$

$$\left(\sum_m {}_{nm}Z'_a\,{}_mJ_a\right)\sin(n\pi x/\lambda)={}_nE_a\times\sin(n\pi x/\lambda)$$

If we multiply by $_aJ_a \sin(n\pi x/\lambda)\,dx$, the element of current at x, gives d_nW, the element of rotor losses + j reactive power for the nth harmonic. Integrating over the whole rotor

$$P\int_0^\lambda \sum_m {}_{nm}Z'_a\,{}_mJ_a \sin^2(n\pi x/\lambda)dx = {}_nW\,{}_nJ_a \quad (39)$$

$$(P\lambda/2)\,{}_nJ_a \sum_m {}_{nm}Z'_a\,{}_mJ_a = {}_nW$$

Now the total current that encircles x of the mth harmonic is

$${}_mJ_a \int_a \sin(m\pi x/\lambda)dx$$

Since this flows through one turn, it is also the magnetomotive force of the secondary

$$MMF_2 = (\lambda_m J_a/\pi m)\cos(m\pi x/\lambda) \quad (40)$$

The magnetomotive force of the primary is $(4/\pi)\,{}_mI_{2a}\cos(m\pi x/\lambda)$. Equating primary and secondary magnetomotive force

$${}_mJ_a = (4m/\lambda)\,{}_mI_{2a} \quad (41)$$

Substitution in equation 39 gives

$${}_nW = (8P/\lambda)n\,{}_nI_{2a}\sum_m {}_{nm}Z'_a\,{}_mI_{2a} \quad (42)$$

Thus ${}_nW$ has the form

$${}_{11}Z_a\,{}_1I_{2a}\,{}_1I_{2a} + {}_{22}Z_a\,{}_2I_{2a}\,{}_2I_{2a} + \ldots$$

and if corresponding products of I_{2a} are equated to those of J_a

$${}_{nm}Z_a = (8P/\lambda)n\,{}_nI'_a\,{}_mI'_a\,{}_{nm}Z'_a \quad (43)$$

where the D's that make up ${}_{nm}Z'_a$ are given in terms of one inch of rotor periphery. Since, in equation 25

$$Z_1 = {}_1Z_a\lambda P/S_s$$

$${}_{nm}Z'_a = {}_{nm}Z''_a\lambda P/S_s$$

and

$${}_{nm}Z_a = (8P^2/S_s)n\,{}_nI'_a\,{}_mI'_a\,{}_{nm}Z''_a \quad (44)$$

where ${}_{nm}Z''_a$ is given in terms of impedance per bar. The formula for phase b is obtained, as usual, by substituting quantities in b in place of those with subscript a. Thus, we have the system of equations giving the rotor voltage in terms of the harmonic currents, all referred to the stator

$${}_{11}Z_a\,{}_1I_{2a} + {}_{12}Z_a\,{}_2I_{2a} + {}_{13}Z_a\,{}_3I_{2a} + \ldots = {}_1E_a$$

$${}_{21}Z_a\,{}_1I_{2a} + {}_{22}Z_a\,{}_2I_{2a} + {}_{23}Z_a\,{}_3I_{2a} + \ldots = {}_2E_a \quad (45)$$

The impedances of form ${}_{nm}Z$ can be neglected usually, in which case equation 45 becomes the equations we used in the body of the paper, equations 2 and 3.

As the simplest example, let $Z_1 = {}_0D + {}_2D\cos 2\pi x/\lambda$ which is the impedance given by the air gap represented in equation 1. If we expand ${}_nM_a$ from equation 33 and ${}_nM_b$ from equation 34

$${}_1M_a = (2\,{}_0D - {}_2D)\,{}_1J_a + {}_2D\,{}_3J_a$$
$${}_2M_a = {}_2D\,{}_1J_a + 2\,{}_0D\,{}_3J_a + {}_2D\,{}_5J_a$$
$${}_3M_a = {}_2D\,{}_1J_a + 2\,{}_0D\,{}_3J_a + {}_2D\,{}_5J_a$$
$${}_1M_b = (2\,{}_0D + {}_2D)\,{}_1J_b + {}_2D\,{}_3J_b$$
$${}_2M_b = {}_2D\,{}_1J_b + 2\,{}_0D\,{}_3J_b + {}_2D\,{}_5J_b$$
$${}_3M_b = {}_2D\,{}_3J_b + 2\,{}_0D\,{}_5J_b + {}_2D\,{}_7J_b$$

If we put these values in equation 36

$$(1/2)(2\,{}_0D - {}_2D + K')\,{}_1J_a + {}_2D\,{}_3J_a = {}_1E_a$$
$$(1/2)\,{}_2D\,{}_1J_a + (2\,{}_0D + K'/9)\,{}_3J_a + {}_2D\,{}_5J_a = {}_3E_a$$
$$(1/2)\,{}_2D\,{}_3J_a + (2\,{}_0D + K'/25)\,{}_5J_a + {}_2D\,{}_7J_a = {}_5E_a \quad (46)$$

There are similar equations for b, except that all signs are positive.

Comparing with equation 38, we see that the coefficient of ${}_mJ_a$ is identical with ${}_{nm}Z$. If we desire to express the D's in terms of impedance per bar, as in equation 44, we shall have to multiply K' by $S_s/P\lambda$.

$$K = (4R_r\lambda^2/\pi^2)(S_s/\lambda P) = 4R_r\lambda S_s/\pi^2 P = 4R_r D_r S_s/P^2\pi \quad (47)$$

where D_r = diameter of ring at ends of conductors. From equations 44 and 46 we find, putting

$${}_{nm}G_a = (4P^2/S_s)n\,{}_nI'_a\,{}_mI'_a \quad (48)$$

$${}_{11}Z_a = {}_{11}G_a(2\,{}_0D - {}_2D + K)$$
$${}_{12}Z_a = {}_{12}G_a\,{}_2D$$
$${}_{13}Z_a = 0$$
$${}_{21}Z_a = {}_{21}G_a\,{}_2D$$
$${}_{22}Z_a = {}_{22}G_a(2\,{}_0D + K/9)$$

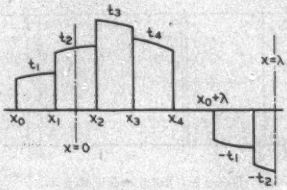

Figure 4. Diagram illustrating notation of stator teeth

$${}_{32}Z_a = {}_{32}G_a\,{}_2D$$
$${}_{31}Z_a = 0$$
$${}_{33}Z_a = {}_{33}G_a\,{}_2D$$
$${}_{32}Z_a = {}_{32}G_a(2\,{}_0D + K/25) \quad (49)$$

In a similar manner we find

$${}_{nm}G_b = (4P^2/S_s)n\,{}_nI'_b\,{}_mI'_b \quad (50)$$

$${}_{11}Z_b = {}_{11}G_b(2\,{}_0D + {}_2D + K) \quad (51)$$

All the other Z_b's are obtained from equation 49 by using G_b instead of G_a.

Computing Bar Constants

The resistance per bar is given by

$$R_B = \rho\sqrt{W^2 + Sk^2}/S_c \quad (51a)$$

where

ρ = resistivity in ohms per inch cube
W = length of rotor
Sk = skew in inches
S_c = section of conductor

The ring resistance per inch is

$${}_nR_r = \rho\,{}_nK_r/S_r \quad (52)$$

where

S_r = section of ring
${}_nK_r$ = Trickey's ring constant[5]
$= (nP/2)(1 - ID/D_r)[1 + (ID/D_r)^{Pn}] + [1 - (ID/D_r)^{Pn}]$

The ring resistance per inch is the leakage reactance is divided into three components:

1. Slot Reactance

$$X_s = 2\pi f 3.19\times 10^{-8} WK_t$$

where

K_s = rotor slot constant[1] (53)

2. Zigzag Reactance

$$X_z = 2\pi f 3.19\times 10^{-8} WT_f/4\Delta$$

where

T_f = tooth face in inches (54)

If the stator slots break the magnetic circuit about the rotor bars, X_z probably will be smaller. Let

$$1/\Delta = {}_0A + {}_2A\cos 2\pi x/\lambda + {}_4A\cos 4\pi x/\lambda + \ldots$$

Then

$${}_0D = R_B + j(X_s + 2\pi f 3.19\times 10^{-8} WT_f\,{}_0A/4) \quad (55)$$

$${}_2D = j_{2\pi} f 3.19\times 10^{-8} WT_f\,{}_2A/4 \text{ and so forth} \quad (56)$$

3. Skew Reactance

$${}_nX_{ska} = {}_nX_s(1 - {}_nC_{sk})$$
$${}_nX_{skb} = {}_nX_s(1 - {}_nC_{sk})$$
$${}_nC_{sk} = [\sin(n\pi Sk/2\lambda)]/(n\pi Sk/2\lambda) \quad (57)$$

${}_nX_{ska}$ is to be added to the value of ${}_{nn}Z_a$ given in equation 49, and ${}_nX_{skb}$ is to be added to ${}_{nn}Z_b$ in equation 51.

Appendix II. Air-Gap Reactance

Figure 4 represents the flux wave.

Let

t_m = turns about stator tooth m
$\rho = 0.4\pi 2.54 A_e/\Delta = 3.19 A_e/\Delta$
A_e = effective area per square inch of pole face

Total Reactance

$$\phi_m = WI\int_{x_{m-1}}^{x_m} t_m \rho\,dx$$
= flux through mth tooth (58)

$$E_m = 2\pi f\ 10^{-8} t_m WI\int_{x_{m-1}}^{x_m} t_m\rho\ dx$$
= voltage induced in winding about mth tooth

$$X_t = (P/I)E_m = 2\pi f\ 10^{-8} PW\sum t_m^2\int_{m-1}^{x_m}\rho\,dx$$
= total reactance linking primary and secondary (59)

If $\rho = {}_0\rho + {}_2\rho\cos 2\pi x/\lambda$

$$X_t = 2\pi f\ 10^{-8} PW\sum t_m^2\left[\int_{m-1}^{x_m} {}_0\rho\,dx + \int_{x_{m-1}}^{x_m} {}_2\rho\cos(2\pi x/\lambda)dx\right]$$

$$X_t = 2\pi f 10^{-8} P W \sum t_m^2 [{}_0p(x_m - x_{m-1}) + ({}_1p\lambda/2\pi)(\sin 2\pi x_m/\lambda - \sin 2\pi x_{m-1}/\lambda)] \quad (60)$$

$$X_t = 2\pi f 10^{-8} P W \sum t_m^2 [{}_0p(x_m - x_{m-1}) + ({}_1p\lambda/\pi) \cos \pi(x_m + x_{m-1})/\lambda \times \sin \pi(x_m - x_{m-1})/\lambda] \quad (61)$$

Harmonic Reactance

${}_nB_a = {}_nB_{a\max} \cos n\pi x/\lambda$ = cosine component nth harmonic flux density

From the formula for Fourier coefficients, we find

$${}_nB_{a\max} = (4/\pi) I\, {}_na = (2/\pi) \times \sum \int_{x_{m-1}}^{x_m} I t_m p \cos(n\pi x/\lambda)\, d(\pi x/\lambda) \quad (62)$$

Let

$$p = {}_0p + {}_1P \cos 2\pi x/\lambda$$

$${}_na = (1/2) \sum \int_{x_{m-1}}^{x_m} {}_0p \cos(n\pi x/\lambda) d(\pi x/\lambda) + (1/2) \sum \int_{x_{m-1}}^{x_m} 2p \cos(2\pi x/\lambda) \cos(n\pi x/\lambda) \times d(\pi x/\lambda)$$

$${}_na = ({}_0p/2n) \sum t_m (\sin n\pi x_m/\lambda - \sin n\pi x_{m-1}/\lambda) + [{}_1p/4(n+2)] \times \sum t_m [\sin(n+2)\pi x_m/\lambda - \sin(n+2) \times \pi x_{m-1}/\lambda] + [{}_1p/4(n-2)] \sum t_m [\sin(n-2) \times \pi x_m/\lambda - \sin(n-2)\pi x_{m-1}/\lambda] \quad (63)$$

$${}_na = ({}_0p/\pi) \sum t_m \cos[n\pi(x_m + x_{m-1})/2\lambda] \sin[n\pi(x_m - x_{m-1})/2\lambda] + [{}_1p/2(n+2)] \sum t_m \cos[(n+2)\pi(x_m + x_{m-1})/2\lambda] \sin(n+2)\pi(x_m - x_{m-1})/2\lambda] + [{}_1p/2(n-2)] \sum t_m \cos[(n-2)\pi(x_m + x_{m-1})/2\lambda] \sin(n-2)\pi(x_m - x_{m-1})/2\lambda] \quad (64)$$

Likewise

${}_nB_b = {}_nB_{b\max} \sin n\pi x/\lambda =$ sin component, nth harmonic flux density

$${}_nB_{b\max} = (4/\pi) I\, {}_nb = (2/\pi) \sum \int_{x_{m-1}}^{x_m} I t_m p \sin(n\pi x/\lambda) d(\pi x/\lambda)$$

With aforesaid permeance, we find, as before

$${}_nb = ({}_0p/2n) \sum t_m (\cos n\pi x_{m-1}/\lambda - \cos n\pi x_m/\lambda) + [{}_1p/4(n+2)] \sum t_m [\cos(n+2) \times \pi x_{m-1}/\lambda - \cos(n+2)\pi x_m/\lambda] + [{}_1p/4(n-2)] \sum t_m [\cos(n-2)\pi x_{m-1}/\lambda - \cos(n-2)\pi x_m/\lambda] \quad (65)$$

$${}_nb = ({}_0p/n) \sum t_m \sin[n\pi(x_m + x_{m-1})/2\lambda] \sin[n\pi(x_m - x_{m-1})/2\lambda] + [{}_0p/2(n+2)] \sum t_m \sin[(n+2)\pi(x_m + x_{m-1})/2\lambda] \sin[(n+2)\pi(x_m - x_{m-1})/2\lambda] + [{}_1p/2(n-2)] \sum t_m \sin[(n-2)\pi(x_m + x_{m-1})/2\lambda] \sin[(n-2)\pi(x_m - x_{m-1})/2\lambda] \quad (66)$$

Let ${}_n\phi_{am}$ = cosine component of flux through mth tooth, nth harmonic.

$${}_n\phi_{am} = W \int_{x_{m-1}}^{x_m} {}_nB_a\, dx = W \int_{x_{m-1}}^{x_m} (4/\pi) I\, {}_na \times \cos(n\pi x/\lambda) dx$$

${}_nX_{am} = (2\pi f 10^{-8}/I) t_{mn} \phi_{am}$ = reactance of mth tooth, nth harmonic, phase a

$$= 2\pi f 10^{-8} (4/\pi^2) W \lambda\, {}_na\, (t_m/n) \times (\sin n\pi x_m/\lambda - \sin n\pi x_{m-1}/\lambda)$$

Summing up the reactance for all the teeth, we have

$${}_nX'_a = 2\pi f 10^{-8} (8/\pi^2) P W \lambda\, {}_na\, {}_nt'_a \quad (67)$$

where

${}_nX'_a$ = total mutual reactance, nth harmonic, phase a. The accent indicates that skew has not been deducted.

$${}_nt_a = (1/2n) \sum t_m (\sin n\pi x_m/\lambda - \sin n\pi x_{m-1}/\lambda) = (1/n) \sum t_m \cos[n\pi(x_m + x_{m-1})/2\lambda] \times \sin[n\pi(x_m - x_{m-1}]/2\lambda]$$

= nth harmonic of effective turns per pole, phase a (68)

Likewise it can be shown that

$${}_nX'_b = 2\pi f 10^{-8} (8/\pi^2) P W \lambda\, {}_nb\, {}_nt'_b \quad (69)$$

$${}_nt_b = (1/2n) \sum t_m (\cos n\pi x_{m-1}/\lambda - \cos n\pi x_m/\lambda) = (1/n) \sum t_m \sin[n\pi(x_m + x_{m-1})/2\lambda] \times \sin[n\pi(x_m - x_{m-1})/2\lambda]$$

= effective turns per pole, nth harmonic, phase b (70)

Each of these reactances must be corrected for skew

$${}_nX_a = {}_nX'_a\, {}_nC_{sk} = {}_nX'_a [\sin(n\pi Sk/2\lambda)] \div (n\pi Sk/2\lambda)$$

$${}_nX_b = {}_nX'_b\, {}_nC_{sk} \quad (71)$$

The amount of reactance that is deducted by this means is added to both the primary and secondary leakage reactance, as in equation 57.

It is convenient to take as the origin a point $\lambda/4$ from the center of the pole, as in Figure 1.

Appendix III. Sample Calculations for a Representative Motor

Partial List of Design Data—Dimensions in Inches

$D = 1.75$
$D_r = 1.65$
$W = 1.25$
$P = 4$
$\lambda = \pi 1.75/4 = 1.375$
$S_c = 0.00815$
$S_r = 0.02445$
$S_s = 25$
$l_1 = 250$
$x_0 = -\lambda/8$
$x_1 = 5\lambda/8$
$\Delta_{min} = 0.015$
$\Delta_{max} = 0.045$
$A_e = 0.815$
$T_r = 0.179$
$K_s = 1.36$
$R_1 = 22$ ohms
$X_1' = 10.0$ ohms
$Sk = 4\lambda/25 = 0.22$

Δ varies as in equation 1; stator iron is continuous.

Primary Reactances

$${}_0A = (1/2)(1/0.015 + 1/0.045) = 44.5$$
$${}_2A = (1/2)(1/0.015 - 1/0.045) = 22.45 \quad (1)$$

$${}_0p = 44.5 \times 0.815 \times 3.19 = 115.6$$
$${}_2p = 22.25 \times 0.815 \times 3.19 = 57.8$$
$$X_t = 377 \times 10^{-8} \times 4 \times 1.25 \times 250^2 \times [115.6(5\lambda/8 - \lambda/8) \times 1.375 + 22.5(1.75/4) \cos(\pi/\lambda)(5\lambda/8 + \lambda/8) \times \sin(\pi/\lambda)(5\lambda/8 - \lambda/8)] = 140.7 \text{ ohms} \quad (61)$$

$${}_1a = 250 \begin{bmatrix} 115.6 \cos(\pi/2\lambda)(5\lambda/8 - \lambda/8) \times \sin(\pi/2\lambda)(5\lambda/8 + \lambda/8) \times \\ (57.8/2 \times 3) \cos(3\pi/2\lambda)(5\lambda/8 - \lambda/8) \sin(3\pi/2\lambda)(5\lambda/8 + \lambda/8) - \\ (57.8/2) \cos(\pi/2\lambda)(5\lambda/8 - \lambda/8) \times \\ \sin(-\pi/2\lambda)(5\lambda/8 + \lambda/8) \end{bmatrix} = 24{,}150 \quad (64)$$

$${}_1l_a = 250 \cos(\pi/2\lambda)(5\lambda/8 - \lambda/8) \times \sin(\pi/2\lambda)(5\lambda/8 + \lambda/8) = 163.2 \quad (57)$$

$${}_1X'_a = 377 \times 10^{-8} (8/\pi^2) 4 \times 1.25 \times 1.375 \times 163.2 \times 24{,}150 = 83.0 \text{ ohms} \quad (67)$$

$$1 - C_{sk} = (1/6)(\pi/2\lambda)^2 (4\lambda/25)^2 = 0.0105 \quad (21)$$

$${}_1X_{sk2} = 0.0105 \times 83.0 = 0.872 \text{ ohm} \quad (19)$$
$${}_1X_a = 83.0 - 0.872 = 82.1 \text{ ohms}$$

Secondary Impedance

$$R_s = \sqrt{1.25^3 + 0.22^3} \times 0.692 \times 10^{-6} / 0.00815 = 1.076 \times 10^{-4} \quad (51)$$

$$R_r = 0.692 \times 10^{-6} / 0.02445 = 0.2825 \times 10^{-4} \quad (52)$$

$$K = 4 \times 0.2825 \times 10^{-4} \times 1.65 \times 25/16 = 0.926 \times 10^{-4} \quad (47)$$

$$X_s = 377 \times 3.19 \times 10^{-8} \times 1.25 \times 1.36 = 0.203 \times 10^{-4} \quad (53)$$

$${}_0D = 1.076 \times 10^{-4} + j(0.293 + 377 \times 10^{-4} \times 3.19 \times 1.25 \times 0.179 \times 44.5/4) 10^{-4} = (1.076 + j\,0.502) \times 10^{-4} \quad (55)$$

$${}_2D = j\,377 \times 10^{-8} \times 3.19 \times 1.25 \times 0.179 \times 22.25/4 = j\,0.1495 \times 10^{-4} \quad (56)$$

$${}_{11}G_a = 4 \times 16 \times 163.2^2/25 = 6.83 \times 10^4 \quad (48)$$

$${}_{11}Z_a = 6.83 [(2 \times 1.076 + 0.926) + j(2 \times 0.502 - 0.1495)] - j\,0.872 = 21.05 + j\,6.71 \quad (49)$$

Computation of the other constants is similar.

Summary of Constants

${}_1X_a = 82.1$ ohms	${}_2X_a = 3.327$ ohms
${}_1X_{sa} = 6.71$	${}_2X_{sa} = 1.519$
${}_1X_{oa} = 88.81$	${}_2X_{oa} = 4.846$
${}_1X_b = 45.72$	${}_2X_b = 1.073$

$_1X_m = 8.37$ $_2X_m = 1.286$

$_1X_{s0} = 54.1$ $_2X_{s0} = 2.359$

$_1R_3 = 21.05$ $_2R_3 = 2.64$

$R_1 = 22$ ohms

$X_1' = 10$

$X_1 = 140.7$

$_1X_a - {}_1X_b = 36.38$

$_1X_b - {}_1X_{s0} = 1.665$

$_2X_a - {}_2X_b = 2.254$

$_2X_{s0} - {}_2X_m = -0.233$

Starting Conditions

$$_1K_{s0} = (82.1/88.8)^2/(1+(21.05/88.8)^2) = 0.810$$

$$_1K_a = (0.810/82.1)(88.8+j21.05) = 0.875-j0.208 \qquad (12)$$

Likewise

$_1K_b = 0.735+j\ 0.2855$, $_1K_a = 0.529+j\ 0.288$, $_2K_b = 0.2025+j\ 0.2265$

The total impedance is

		22 +j	150.7
$-j$ 82.1	(0.875 +j 0.208)	= 17.1 −j	71.9
$-j$ 45.72	(0.735 +j 0.2855)	= 13.08 −j	33.6
$-j$ 3.33	(0.529 +j 0.288)	= 0.96 −j	1.76
$-j$ 1.07	(0.2025+j 0.2265)	= 0.23 −j	0.22
		53.27+j	43.1

$$= 68.5/39°00'$$

$$I = 110/68.7/39°00' = 1.60/-39°00' \text{ amperes}$$

Power factor = cos 39°00′ = 0.778

$W = 110\times1.60\times0.778 = 137$ watts, input

$_1T = (11.3\times4\times0.810\times0.618/60\times82.1\times45.72)1.6^3[1.665(21.05^2-88.8\times54.1)-2\times36.38\times21.05^2]$

$= 0.000256(1.665\times(-4{,}368)-2\times36.38\times442)$

$_1T = 0.000256(-7{,}270-32{,}200)$

$= -10.12$ ounce-inches (13)

The greatest contribution to $_1T$ in this case is seen to be from $_1R_3{}^2(_1X_a - {}_1X_b)$. In the same manner

$_1T = -1.632$ $T = {}_1T+{}_2T = -11.7$ ounce-inches

Although the third harmonic does not affect the current greatly, it is seen to contribute appreciably to the torque. Using the more complete formula of equation 45, $T = -10.6$ ounce inches.

Running Conditions

Let

$S = -0.85$ $1-S^2 = 0.2775$

$-0.85\times21.05\times45.72 = -818$

$-0.2775\times54.1\times82.1 = -1{,}234$

$_1F_a = -2{,}025+j\ 1{,}730$

$j\,21.05\times82.1 = j\,1{,}730$ (6)

$-(-0.85)\times21.05\times82.1 = 1{,}470$

$-0.2775\times88.8\times45.7 = -1{,}125$

$_1F_b = 345+j\,963$

$j\,21.05\times45.7 = j\,963$ (7)

$21.05^2 = 443$

$-0.2775\times88.8\times54.1 = -1{,}333$

$_1F = -891+j\,3{,}010$

$j\,21.05(88.8-54.1) = j\,3{,}010$ (8)

$$_1K_a = (-2{,}052+j\,1{,}730)/(-891+j\,3{,}010) = 0.714-j\,0.470 \qquad (5)$$

$$_1K_b = (345-j\,963)/(-891+j\,3{,}010) = 0.262-j\,0.193 \qquad (6)$$

If $_2K_a$ and $_2K_b$ are computed and equation 9 is used again

$Z_0 = 93.1/56°20'$

$I = 1.18/-56°20'$ amperes $= 0.653-j\,0.981$ ampere

Power factor = 0.55

Input = 71.4 watt (iron losses to be added)

$_1U = 0.714$ $_1u = 0.470$

$_1V = 0.262$ $_1v = -0.193$

$_1U_1V - {}_1u_1v = 0.714\times0.262-0.470\times0.193 = 0.0961$

$_1T = (11.3\times4/60)1.18^2[(0.262-0.0961)\times82.1-(0.714-0.0961)45.7] = -15.3$

Likewise

$_2T = 2.95$

$T = {}_1T+{}_2T = -12.3$ ounce inches

Output = $0.001782\times0.85\times12.3 = 0.0186$ horsepower

Output = $0.0186\times746 = 13.9$ watts

Efficiency (disregarding iron losses) = $13.9\times71.4 = 19.5$ per cent

Iron Losses

Let

Hysteresis coefficient, $\eta = 0.003$

Conductivity of iron = 10^9

Thickness of laminations = 0.03

Cross section of half of flux path = 0.390

Volume of iron = 10.3

Maximum flux density = B_m

Hysteresis loss per cubic inch = $_hw$

Eddy-current loss per cubic inch = $_ew$

$_hw = 8.3\times10^{-3}\times0.003\times60B_m{}^{1.6} = 1.495\times10^{-3}B_m{}^{1.6}$ watts per cubic inch

$_ew = 4.18\times10^{-18}\times10^{18}\times0.03^2\times60^2B_m{}^2 = 1.353\times10^{-16}B^2$ watts per cubic inch

To obtain the voltage drop due to the flux, deduct the primary IR (current resistance) drop from the applied voltage

$E_\phi = 110-22\times1.18/-56°20'$

$= 98.1/12°44'$

$\phi_p = E\phi/2\pi f\,10^{-8}{}_1p$ P = flux per pole

$\phi_p = 98.1/377\times10^{-8}\times250\times4 = 2.60\times10^4$

$B_m = 2.60\times10^4\times\sqrt{2}/2\times0.390 = 4.71\times10^4$ lines per square inch

$_hw = 1.495\times10^{-3}(4.71\times10^4)^{1.6} = 0.449$

$_ew = 1.353\times10^{-16}(4.71\times10^4)^2 = 0.301$

0.750 watt per cubic inch

$W = 10.3\times0.750 = 7.73$ watts, total iron loss

$7.73/98.1/12°44' = 0.0788/-12°44'$

$= 0.0770-j\,0.0146$ = iron-loss current

$0.653-j\,0.981+0.0770-j\,0.0146 = 0.730-j\,0.996 = 1.24/-53°45'$ = total current

71.4+7.8 = 79.2 watts, total input

13.9/79.2 = 17.9 per cent efficiency

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An Eight-Year Investigation of Lightning Currents and Preventive Lightning Protection on a Transmission System

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SOME 10 or 12 years ago effective lightning protection began to be applied to transmission lines, and, about the same time, an inexpensive measuring device (the surge-crest ammeter) was developed.[1] On one transmission system this low-cost device has been applied to every structure in entire lines and has produced definite numerical evidence of the performance of the protection provided.

It is shown that on the system studied, the distribution of lightning strokes occurs at random, and that there are great variations in the number and intensity of strokes from year to year. The numerical data show that the gain would be small from protection of single structures or sections of lines. The data also make it possible to estimate long-time line performance from short-time records. The surge impedance of an overhead ground wire is indicated to be less than 235 ohms instead of the generally accepted value of 400 to 500 ohms

The counterpoise arrangements on the lines in question vary from a single wire to eight wires in multiple. There is no evidence to show that one arrangement is better than another, as long as the resulting ground-resistance value is the same. The bonding of structures at crossings and parallels shows no tendency to spread trouble from one structure to another. Arresters connected to well-protected lines were seldom caused to operate, and, when they did, the currents in most cases were small.

Scope of Field Investigation

The installation of surge-crest-ammeter links was begun on a system in Pennsylvania and Maryland in June 1934, with additional installations being made every succeeding year. By the end of 1942, brackets were installed on transmission-line steel structures, lightning arresters, overhead ground wires, lightning rods, and a steel flagpole. The aggregate exposure of the links has been considerable on the lines, amounting to 13,227 tower-years and 1,776 mile-years with 5,501 bracket records obtained. The exposure on the lightning arresters connected at the terminals of the lines has been 155 bank-years, with 54 records obtained. No significant records were obtained from the few miscellaneous bracket installations.

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Table I. Variation in Total Number of Strokes Recorded Yearly on Five Transmission Lines

Year	Strokes Recorded	Ratio to Five-Year Average
1938	239	1.05
1939	283	1.25
1940	253	1.11
1941	163	0.72
1942	199	0.88
Average	227	

Frequency of Strokes to Lines

Two 220-kv lines, one 132-kv line, and two 66-kv lines cover the area served by the system. The stroke records from these five lines, having an aggregate length of 228 miles, are taken as giving a representative picture of lightning conditions on the system. Table I shows how the number of strokes recorded on these lines varied from year to year. The ratio of the yearly maximum of recorded strokes to the minimum is 1.74.

When the records of individual lines are examined, the variations become more pronounced. This is demonstrated in Table II, which is the record for the four transmission lines on which tower lightning currents have been measured for the longest time. As is to be expected, the range of yearly variations is greater for single lines than for the system as a whole. Also, the longest line does not show so wide a range in the number of recorded strokes as do the shorter lines. Beyond these generalizations, the data show random behavior. For instance, in Figure 1 are given records of two comparable lines, both lying in a more or less east–west direction and having very nearly the same stroke density. In 1938 line *C* received its peak number of strokes for its seven years of record, while line *D* received the lowest number of strokes for the same time.

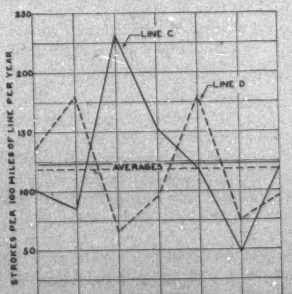

Figure 1. Strokes to two 66-kv lines

These wide variations are indicative of the difficulty of judging the value of any lightning-protective scheme from short-time field-performance data. Table III shows how the average recorded stroke frequency for a small number of consecutive years can be quite far from representative of the long-time experience. In this table, seven- and eight-year records are assumed to be representative samples of the long-time record. This assumption seems reasonable for all practical purposes.

As was to be expected, the average stroke frequency for any number of consecutive years usually did not deviate from the period average as widely on line *A*, 91.8 miles long, as it did on the shorter lines. A long line has a good chance of being in the path of most local thunderstorms, some of which might miss shorter lines.

In Table III, the large ratios of maximum to minimum number of strokes recorded yearly help explain the common experience of a line behaving well one year and poorly the next.

Frequency of Strokes to Individual Towers

Repeated lightning trouble at a given tower during a relatively short period of one or two years often is considered indicative of a location particularly sub-

Table II. Recorded Strokes to Lines Per 100 Miles Per Year

	Line A 220 Kv	Line B 132 Kv	Line C 66 Kv	Line D 66 Kv	Average Values
Length of line in miles	91.8	33.8	29.4	22.8	
Period of record in years	8	8	7	7	
Average strokes for period	95	135	123	119	118
Maximum in one year	129	219	232	180	190
Ratio to period average	1.36	1.62	1.89	1.51	1.61
Minimum in one year	59	86	49	66	65
Ratio to period average	0.62	0.64	0.39	0.55	0.55
Ratio of yearly maximum to yearly minimum	2.19	2.54	4.85	2.73	2.92

1,364 mile-years of line are represented by above record.

System average strokes per 100 miles of line per year is 113 for five observed lines totaling 1,617 mile-years of experience.

Table III. Ratio of Average Stroke Frequency for Consecutive Years to the Average for an Entire Period of Record

Indicated Number of Consecutive Years		Period of Record (Years) 8 Line A	8 Line B	7 Line C	7 Line D
One year records	Maximum	1.36	1.62	1.89	1.52
	Minimum	0.62	0.64	0.39	0.56
Averages for two consecutive years	Maximum	1.29	1.36	1.57	1.34
	Minimum	0.77	0.70	0.68	0.68
Averages for three consecutive years	Maximum	1.18	1.31	1.37	1.07
	Minimum	0.82	0.76	0.79	0.96
Averages for four consecutive years	Maximum	1.06	1.28	1.20	1.10
	Minimum	0.85	0.86	0.90	0.88
Averages for five consecutive years	Maximum	1.10	1.19	1.13	1.11
	Minimum	0.89	0.93	1.04	0.87
Averages for six consecutive years	Maximum	1.08	1.10	1.03	1.03
	Minimum	0.91	0.96	1.00	1.03
Averages for seven consecutive years	Maximum	1.02	1.05		
	Minimum	0.95	1.04		

ject to lightning. Inasmuch as the records on lines *A* and *B* have been kept for eight complete years, some data are available which show what can be expected. Table II shows that a unit length of line *A* is struck, on the average, about 70 per cent as often as a unit length of line *B*. The effect of the greater number of strokes to line *B* is shown in the greater percentages of towers struck and struck more frequently (Table IV). The percentages of towers of both lines that were struck one, two, and three times are nearly equal.

There were 104 cases on lines *A* and *B* during the eight years of record in which an individual tower was struck two years in succession, 15 cases in which a tower was struck three consecutive years, and only three cases in which individual towers were struck four years in succession.

Towers rarely were struck more than once in a single year. On lines *A* and *B* there were 63 cases in which towers were struck twice in a single year, and only one case in which three strokes to an individual tower were recorded.

Table V shows that towers can pass through several years without being struck. If this should occur where no lightning-recording device is used, it might be inferred that the lightning protection is quite good, when in reality there has been an absence of strokes. A period of freedom from lightning strokes may be followed by a period of frequent strokes. The detailed records from the towers of these two lines show all types of distribution of strokes during the eight-year period. From these data it appears that no tower is more subject to lightning than another except by chance.

Variations in Lightning Intensity

In addition to the variation in the number of strokes striking a line, a variation in their intensity also affects performance. Figure 2 shows the distribution of tower currents during a long period of time.

In any one year the percentage of tower currents exceeding any given value may be quite different from the average for a long period. This is shown in Table VI. Since both the stroke frequency and intensity seem to be random phenomena, a number of years sometimes elapses between flashovers on a fairly well-protected line that is faulted by only high-intensity strokes. The other extreme condition, in which there are a number of flashovers in one year, or even during one storm, sometimes occurs. A rare instance of this latter type of trouble occurred during 1942 on the 66-kv line *C*, when five towers covering a distance of 1.9 miles experienced flashovers, although only one simultaneous double-circuit tripout occurred.

An interesting and perhaps significant phenomenon appears in Figure 2. For some years on this distribution curve of tower currents, the points for 30,000 amperes and less have followed a wavy line such as shown by the broken line in Figure 2. Up to this time,[2] the apparent irregularity in the points was thought to be the result of insufficient data, but now, with 1,987 cases accumulated, this original explanation appears to be incorrect. All of the data obtained thus far (1934–42) have been plotted in 5,000-ampere groups in Figure 3. It will be seen that the maximum number of cases has occurred in the 5,000- to 10,000-

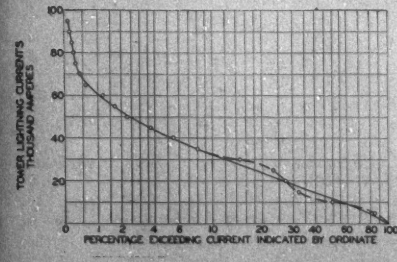

Figure 2. Distribution of 1,987 currents measured in towers believed struck by lightning

Table IV. Number of Times Individual Towers Have Been Struck by Lightning During an Eight-Year Period

Number of Times Struck	Towers Struck the Indicated Number of Times — Line A Number	Line A Per Cent	Line B Number	Line B Per Cent
0	115	24.1	23	12.9
1	163	34.2	63	35.2
2	106	22.2	41	22.9
3	71	14.9	26	14.5
4	15	3.2	19	10.5
5	5	1.0	4	2.3
6	2	0.4	2	1.1
7	0	0	1	0.6
	477		179	

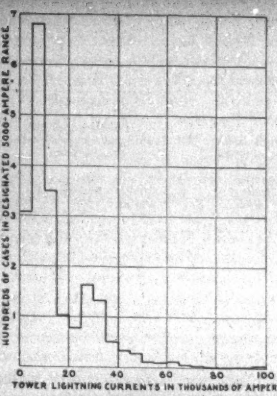

Figure 3. Range distribution of 1,987 currents in towers believed struck by lightning 1934–42

Table VII. Ratio of Sum of Four Leg Currents, Representing Probable Tower Current, to Four Times the Single-Leg Current

Tower Current (Four Times Single-Leg Current)	Number of Leg Records	Ratio of Sum of Four Leg Currents to Four Times Single-Leg Current		
		Average	Median	Range
1– 1,000	28	5.39	2.42	1.42–49.5
1,001– 2,000	21	3.78	2.69	0.93–17.8
2,001– 5,000	46	1.24	1.07	0.25– 3.75
5,001– 7,500	48	0.89	0.82	0.25– 2.88
7,501–10,000	59	1.13	1.02	0.25– 4.13
10,001–15,000	87	1.01	0.97	0.30– 1.85
15,001–20,000	17	1.17	0.91	0.33– 4.25
20,001–25,000	13	0.89	0.88	0.28– 1.25
25,001–30,000	23	0.82	0.84	0.47– 1.10
30,001–35,000	17	0.80	0.82	0.26– 1.27
35,001–40,000	9	1.03	1.01	0.73– 1.28
40,001–45,000	1	1.13	1.13	
45,001–50,000	4	0.89	0.89	0.82– 0.95
50,001–55,000	4	0.85	1.00	0.25– 1.14
55,001–60,000	5	0.94	1.01	0.77– 1.03
60,001–65,000	3	0.97	0.97	0.93– 1.02
65,001–70,000	2	0.93	0.93	0.88– 0.98
76,000	1	0.52	0.52	
80,001–85,000	2	0.37	0.37	0.25– 0.48
114,000	1	0.57	0.57	
	391			

ampere range, with a secondary peak occurring in the 25,000- to 30,000-ampere range. To investigate whether or not this phenomenon is the result of some unusual records obtained during the early part of the period of study which influenced the entire set of data, the data from individual years in which records were complete were plotted by percentage in Figure 4. The primary peak is quite pronounced every year in the 5,000- to 10,000-ampere range. The secondary maximum in the 25,000- to 30,000-ampere range is quite apparent in the records from 1935, 1938, 1940, 1941, and 1942. It is less prominent in the 1937 and 1939 records. The secondary maximum occurs in the 20,000- to 25,000-ampere range in 1936.

Table V. Towers Not Struck in Successive Years During an Eight-Year Period

Years in Succession in Which a Tower Was Not Struck	Number of Cases	
	Line A	Line B
1	200	122
2	167	65
3	133	62
4	98	40
5	67	27
6	57	19
7	38	13
8	115	23

Table VI. Range of Per Cent of Tower Currents in Single Years Exceeding Indicated Value

Tower Amperes	Range of Yearly Per Cent*		Average Per Cent 1934–42
	Minimum	Maximum	
10,000	37.5	65.4	50
20,000	13.4	39	27.1
30,000	6.2	20	14.8
40,000	0.8	9.2	5.5
50,000	0	4.1	2.3
60,000	0	2.0	1.2
70,000	0	1.2	0.4
80,000	0	0.8	0.25
90,000	0	0.6	0.15
100,000	0	0	0

* Eight-year record, 1935–42. Records were not obtained for the entire 1934 lightning season, but the records obtained in that year are included in the average values given in the last column.

This analysis makes it appear that the wavy form of the broken line curve in Figure 2 is a more accurate representation of the distribution of tower currents below 35,000 amperes than is the straighter line. It appears that there are two principal types of lightning discharges as far as tower currents are concerned. Most of one type produce tower currents in the 5,000- to 10,000-ampere range, and most of the other type produce them in the 25,000- to 30,000-ampere range.

Division of Lightning Currents in Legs of Towers

Most of the tower lightning currents have been measured in towers where surge-crest-ammeter brackets have been mounted on only one leg. The tower current in such cases has been assumed to be four times the current measured in the leg having the bracket. Of principal interest are the records from towers which it is believed have been struck by lightning or are adjacent to struck spans of overhead ground wire, because it is these towers which are subject to flashovers.

It is believed that there have been 104 times when towers provided with surge-crest-ammeter brackets on all four legs have been hit. These 416 records permit an estimate to be made of the errors involved when the tower current is computed from the current in a single leg.

Each of the 104 sets of records has been analyzed by first adding the four leg currents to obtain the nominal tower current. Then, each record was treated as if it were the only one available from a tower. In Table VII are data on the ratio of the sum of the four leg currents in a tower to the product of four times the single leg currents taken individually. If one assumes that the sum of the four leg currents is a good representation of the true tower current, the probable tower current can be obtained from a single-leg record by the relation:

Probable tower current = 4 × leg current × ratio from Table VII

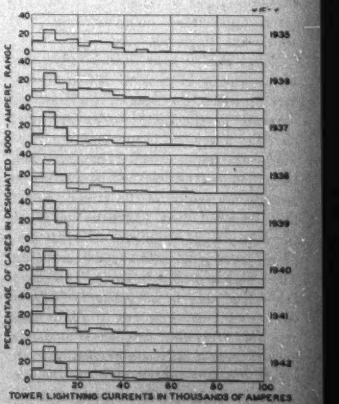

Figure 4. Range distribution of tower lightning currents by years

Table VIII. Lightning Disturbances on Parallel 66-Kv Lines

40 Miles—415 Towers

	Observation Period (Years of Record)											
	1918–31 14 (No Grounding)			1932–34 3 (Single Bonds Towers 5–90)			1935–38 4 (Single Bonds Towers 6–332)			1939–42 4 (Double Bonds and Counterpoise—Towers 6–415—Entire Line)		
	Number During Period	Average Number Per Year	Per Cent	Number During Period	Average Number Per Year	Per Cent	Number During Period	Average Number Per Year	Per Cent	Number During Period	Average Number Per Year	Per Cent
Disturbances involving one circuit	91	6.5	46.5	11	3.7	31.4	9	2.3	47.4	2	0.5	50
Disturbances involving two circuits on only one line	95	6.8	48.5	15	5.0	42.9	8	2	42.1	0	0	0
Disturbances involving circuits on both lines	10	0.7	5.0	9	3.0	25.7	2	0.5	10.5	2	0.5	50
Totals	196	14	100	35	11.7	100	19	4.8	100	4	1	100

For instance, there was a case of flashover in which the tower lightning current was calculated from one leg-current record as being 13,400 amperes. This current lies in the range 10,001 to 15,000 amperes in Table VII. The median ratio is 0.97 in this range, which indicates that there is an even chance that the tower current was more or less than $0.97 \times 13{,}400$ amperes $= 13{,}000$ amperes. However, experience with 87 records in this range indicates that the current possibly may have been anywhere in the range 0.30 to $1.35 \times 13{,}400$ amperes, or between 4,000 and 24,300 amperes.

The values of the median ratio being near unity in most cases in Table VII indicates that, on the average, results throughout most of the range of the currents measured are of fairly uniform accuracy. The low values of the median ratio for tower currents above 70,000 amperes and the high values below 2,000 amperes suggest that currents indicated in these ranges by single-leg records are often appreciably different from four times the single-leg value.

There were 25 cases in which there was no indication of current in a tower leg but in which the sum of the four leg currents in the given tower indicated that the tower had been struck by lightning. In these cases, if brackets had been mounted only on the legs yielding no records, no record of the strokes would have been obtained. Actually the tower currents ranged from 800 to 6,200 amperes, averaging about 2,200 amperes. These data and those in Table VII suggest that there may be $25/(416-25) \times 100 = 6.4$ per cent more strokes to a line than indicated by the surge-crest-ammeter links if there is only one bracket on each tower. It thus appears that the absence of a record on a tower having a single bracket does not mean necessarily that the tower has not been struck by lightning. The data also imply that it probably would be quite difficult to arrive at a satisfactory constant factor to account for currents carried by tower cross members, because the current distribution in cross members probably varies as widely as that in the legs.

Effect on Flashovers of Bonding Adjacent Towers

There have been three instances of flashover on neighboring towers where footings are bonded with buried conductors. Two of these were simultaneous flashovers on two lines carrying two circuits each and situated on the same right of way with 50 feet separation. Table VIII summarizes the lightning experience on these lines in the 25-year period 1918–42. During this period the lines operated 14 years without bonding. When adjacent towers on about three quarters of the line were bonded, the four-year period 1935–38 showed only 4.8 disturbances per year as compared to an average of 14 in the period without bonding.

Before the bonding was installed there were 0.7 disturbance per year involving circuits on both lines, and after the bonding was installed there were 0.5 disturbance per year of this type.

The third instance of flashover occurred on a tower of line *C*, which is shielded by the much taller tower of line *B*. The footings of the two towers are bonded together. When flashover occurred on the line-*C* tower, there was no flashover of the line-*B* tower, although the latter tower current was about 80,000 amperes. This current gives a tower-footing resistance drop of around 930-kv. Apparently the 132-kv tower was struck, but the potential of the 66-kv tower was raised through the bonding to a level sufficient to flash over. During the period of record previous to the flashover in 1942, there were ten strokes to the towers at this intersection without any flashover. The tower currents were all 38,000 amperes or less.

These three instances of trouble at bonded towers raise a question about the value of bonding neighboring transmission towers, but the complete record of tower lightning currents makes it appear that bonding is helpful in reducing the total number of flashovers on adjacent towers if the bonding can reduce footing resistances. There seems to be no effect of bonding on multiple-line disturbances. Table VIII shows the total number of disturbances reduced further by the installation of counterpoise. The number of simultaneous flashovers appears to remain constant, but becomes a greater percentage of the total number of disturbances with improvement of grounding.

Efficacy of Continuous Counterpoise

Examination of Table IX shows that as many as eight continuous counterpoise

Table IX. Flashovers Believed Caused by Strokes to Towers or Overhead Ground Wires on 66-Kv Lines Provided With Preventive Protection

Type of Counterpoise	Number of Cases	Tower Footing (Ohms)	Ratio of Footing Resistance Drop to Tower Flashover Level
8 continuous	2	3.6, 5	0.26, 0.37
6 continuous	2	10.5, 17	0.75, 0.91
5 continuous	2	4.6, 9	0.26, 0.38
4 continuous	2	13.8, 19	0.82, 1.16
4 continuous 3 400 feet +	2	11.8, 17.2	1.25, 1.30
2 continuous 3 400 feet +	1	5.4	0.38
	11		

There has been one flashover on a 132-kv tower (137 feet high):

Footing (ohms) 12.2

Footing resistance drop / Tower flashover level = 0.41

Counterpoise: Four continuous + 4 300 feet

connected to a 66-kv tower do not produce a surge impedance low enough to prevent flashovers. These lines have insulator flashover values of 565–635 kv with a $1^1/_2 \times 40$-microsecond wave. In a number of cases the ground resistance was quite low, making the tower potentials based on the product of tower current times tower-footing resistance only a small fraction of the value expected to produce flashover. Since flashover occurred with such low footing resistance it seems reasonable that the inductive reactance drop was largely responsible and that the footing resistance might be higher without additional flashovers occurring. Measurements show that the omission of the four inner conductors of the counterpoise system, where the ground resistance is 3.6 ohms, would raise the ground resistance of the remaining counterpoise, consisting of four conductors, to about 4.5 ohms. The inner conductors were originally installed in the hope that the surge impedance would be reduced sufficiently to prevent flashovers. The experience listed in Table IX shows that this hope was not realized. It thus appears that no benefit is derived from adding counterpoise wires after the ground resistance has been reduced to the optimum value.[3]

Line *B* has an insulator flashover level of 1,015 kv. The only flashover on this line was at a tower 137 feet high, which is about twice the height of the 66-kv towers. It seems likely that the surge impedance added by the greater tower height contributed to the conditions causing flashover. The product of tower-footing resistance times tower current is only 41 per cent of the theoretical tower potential required for flashover. The eight-year record of line *B* indicates that multiple counterpoise systems having the optimum ground resistance of ten ohms or less prevented flashovers.

The 220-kv lines have an insulator flashover level of 1,605 kv, for which the optimum footing resistance is 16 ohms.[3] Since very low footing resistances were not required, an experimental installation of single counterpoise, continuous in both directions to the next adjacent towers, was made at 38 towers of a 220-kv line. The lightning-current records have been kept on these towers for nine years, making a total of $9 \times 38 = 342$ tower years of record without flashover. Sixty-four strokes were recorded on the towers during this period, producing tower currents as great as 98,000 amperes. The footing resistances did not exceed 20 ohms. The data seem to indicate that towers having an insulator flashover level of about 1,600 kv are quite well protected by single continuous counterpoise, provided this type of grounding will bring the footing resistances down to the optimum value.

Estimated Maximum Apparent Surge Impedance of an Overhead Ground Wire

Table X gives 17 instances when tower currents of about 30,000 amperes or greater have been recorded in two adjacent towers of a line and the currents have not differed from each other by more than 25 per cent of the larger tower current. A pair of records of this type has been interpreted as resulting from a stroke to an overhead ground wire about midway between towers. The current in the overhead ground wire is probably as great as, or greater than the indicated tower current, because some current probably flows in the overhead ground wire, or wires, past the recording tower and does not affect the surge-crest-ammeter links.

Since no tripouts occurred in any of these cases, there is assurance that no flashovers occurred at any of these locations. Incidentally, flashovers causing tripouts have been at towers, not in mid-span. In Table X the voltage required to flash over the mid-span spacing and the probable minimum value of the lightning current in the overhead ground wire are given. The probable upper limit for the surge impedance of the overhead ground wire is the foregoing voltage divided by the corresponding tower current. The average value of the surge impedance, calculated in this way, is 236 ohms, the median is 228 ohms, and the range is from 139 to 323 ohms. These values for the surge impedance of a conductor in air are appreciably less than the theoretical value of 400 or 500 ohms often quoted. Of more practical interest is the implication from these data that mid-span clearances may not need to be so great as often are allowed. Perhaps the prevention of sleet and snow troubles, rather than the prevention of mid-span lightning flashovers, should be the controlling factor in determining mid-span clearances.

Table X. Estimate of Maximum Value of Surge Impedance of an Overhead Ground Wire

Mid-Span Spacing Between Overhead Ground Wire and Nearest Line Conductor	Span Length in Feet	Nominal Voltage (Kv) to Produce Flashover at Mid-Span (1 Microsecond Front)	Lightning Currents in Adjacent Towers	Maximum Surge Impedance (Ohms) Without Flashover
15.8	810	5,020	36,200 35,200	139
23.8	780	7,560	33,200 30,000	228
27.2	1,020	8,650	30,000 30,000	289
28.5	790	9,060	41,600 41,200	223
28.5	915	9,060	34,800 31,200	261
29.5	1,250	9,380	40,400 39,200	232
29.9	1,100	9,500	43,200 38,000	220
30.1	980	9,560	47,200 39,200	203
30.1	1,000	9,560	34,800 31,200	275
30.1	1,000	9,560	48,800 40,000	196
30.1	1,000	9,560	47,600 38,200	200
31.6	1,150	10,050	42,800 33,600	235
32.1	1,210	10,200	35,000 30,400	292
32.8	1,250	10,400	37,600 30,600	276
33.3	1,290	10,600	32,800 29,200	323
33.8	1,320	10,750	53,200 42,400	202
34.2	1,750	10,900	50,400 44,400	216

Table X. Estimate of Maximum Value of Surge Impedance of an Overhead Ground Wire

Comparison of Estimated and Actual Lightning Performance

Published literature on lightning protection indicates over 20 factors probably affecting the estimated lightning performance of a transmission line (see appendix). The individual effect of most of these factors is known only qualitatively, and so it is practically hopeless to include them in any estimating method. Relatively simple calculations were attempted in 1937 for estimating the line interruptions which might be expected as a result of lightning.[2,4] From the records available,

Table XI. Estimated and Actual Lightning Outages

Line	Years of Record	Lightning Outages Per Year		Error (Per Cent)
		Actual	Estimated	
A—220 kv	11	0.09	0.014	**
F—220 kv	5	0	0*	**
B—132 kv	8	0.13	0.05	**
E— 66 kv	4	1	1	0
C— 66 kv	5	1	1.3	+30
Before improvement (1928–36)	9	17.9	21.0	+17
D— 66 kv				
Before improvement (1929–34)	6	19.3	20.6	+ 7

* Does not include a one-mile section where there are no overhead ground wires.

** It will take many more years of operation to check the accuracy of estimates for these lines because flashovers so seldom occur.

Table XII. Efficiency of Preventive Lightning Protection During Period of Study With Surge-Crest-Ammeter Links

Line	Years of Record	Lightning Outages*	Tripouts Per 100 Miles of Line Per Year	Recorded Strokes	Efficiency of Protection (Per Cent)
A—220 kv	8	0	0	696	100
F—220 kv	5	0	0	223	100
B—132 kv	8	1	0.39	354	99.7
C— 66 kv					
Before improvements	2	37	63	55	33
After improvements	5	5	3.4	198	97.5
Suspension towers		4**		143	97.2
Strain towers		4**		55	92.7
E— 66 kv (Two lines on one right of way)	4	4	1.3	236	98.3

* Single, double, and triple circuit tripouts. ** Flashovers.

the method seems to work well for shielded lines. As a further check, and to determine if the method also applies to unprotected lines, additional calculations were made for lines *C* and *D* before they were improved. The results are shown in Table XI.

Line *D*, before it was improved, is of particular interest because of its non-uniformity. The line is 22.8 miles long, and approximately 2.1 miles on each end were provided with a single overhead ground wire. There was no auxiliary grounding anywhere on the line. Detailed calculations for estimating the performance are given in the appendix, and indicate that 20.6 tripouts per year could be expected. This is an error of only seven per cent from the actual experience, as shown in Table XI.

Efficiency of Preventive Protection

The efficiency of the protection provided by the combination of insulation, grounding, and shielding can be calculated from the stroke and tripout records. Efficiency of protection is the ratio, expressed in per cent, of the number of strokes not causing tripouts to the total number of strokes. Table XII gives the record for all lines. The record of line *D* is omitted from this table, because this line is provided with a Petersen coil as well as preventive protection. It has suffered no lightning troubles during five years' operation with this double protection.

The better efficiency of protection for the suspension towers of line *C* as compared to the strain towers is probably the result of the better shielding on the former type of towers.[8] From the number of flashovers believed the result of poor shielding, the efficiency of shielding can be estimated as 99.2 per cent for the suspension towers and 96.4 per cent for the strain towers.

The 100 per cent protection experienced on the 220-kv lines during the years of surge-crest-ammeter link recording cannot be interpreted as meaning that the lines are "lightningproof." Line *A* tripped out in 1933. The grounding on the line has been improved since, but on the basis of 11 years' operation and an estimated 960 strokes, the efficiency of protection is about 99.9 per cent. This record emphasizes the need for long periods of study of well-protected lines, since flashovers occur so seldom that the strokes causing them might be considered freaks. It is evident that some further improved protection will have to be developed if perfection is to be attained.

Discharges Through Lightning Arresters

Surge-crest-ammeter brackets are mounted on 26 banks of lightning arresters and one set of 220-kv expulsion gaps. Table XIII summarizes the records obtained since the first brackets were installed in 1935. It will be noted that 35 of the 53 arrester discharges, or 66 per cent, are less than 1,000 amperes. Only three of the discharges, or six per cent, exceed 2,700 amperes.

Summary

1. The recording of lightning currents with surge-crest-ammeter links began in 1934. In the ensuing years through 1942, 5,501 bracket records have been obtained from transmission towers aggregating 13,227 tower-years of exposure. There have been 54 sets of records from lightning arresters, obtained during 155 bank-years of experience.

Table XIII. Summary of Discharges Through Lightning Arresters

Arrester Type	Period of Record in Stack- or Bank-Years	Discharge (Amperes)	Distribution of Records	
			Number	Per Cent
220-kv one-phase stacks	27	200	2	50
		2,100	1	25
		2,500	1	25
220-kv one-phase expulsion gaps	6	9,700	1	100
132-kv one-phase stacks	20	600	1	100
66-kv three-phase banks	68	1– 500	10	41.6
		501–1,000	6	25.0
		1,700–2,000	3	12.5
		2,200	1	4.2
		2,600–2,700	2	8.3
		5,400	1	4.2
		7,400	1	4.2
66-kv one-phase stacks	198	1– 500	13	54.1
		800	3	12.5
		1,050	2	8.3
		2,100–2,400	2	8.3
		2,600	2	8.3
		4,500	2	8.3
			54	

2. Based on an eight-year period of record in one case and a five-year period in the other, two similar 220-kv lines running in a generally north–south direction experienced the same average number of strokes per year within approximately seven per cent. Two similar 66-kv lines lying in an east–west direction experienced the same average number of strokes, within about three per cent, during a seven-year period.

3. A 132-kv line, having about the same span lengths as a 220-kv line but lying in a more or less northwest–southeast direction within about two miles of a river throughout its length, experienced on the average about 40 per cent more strokes per unit length than the 220-kv line during an eight-year period.

4. The maximum number of strokes recorded on one of the transmission lines in one year was 4.9 times the minimum number recorded in another year. The maximum number on this line occurred in the same year that the minimum number occurred on a comparable line.

5. The strokes in single years to a line deviated up to 89 per cent from the seven- or eight-year averages. The average number of strokes recorded in two or more consecutive years did not deviate so much as this from the long-time records. With these experience records, it is possible to estimate the long-term experience on a line from the experience of a few years.

6. The number of strokes recorded in single years on a line 92 miles long did not vary so much as those recorded on shorter lines. It may be inferred from this that the number of lightning troubles will not vary so much from year to year on long lines as it will on shorter ones.

7. The data for tower lightning currents show most records in the range from 5,000 to 10,000 amperes with a secondary maximum in the 25,000- to 30,000-ampere range. This suggests that there may be two types of lightning discharges, most of each type producing tower currents in different ranges.

8. The majority of towers were not struck more than once a year, but it is not unusual for a tower to be hit twice in one season. Only one tower during an eight-year period on two lines (5,248 tower years) has been struck three times in one year. More than three strokes per year has not been recorded on any tower under observation.

9. Of 656 towers observed for eight consecutive years, 138, or 21 per cent, did not produce records indicating that they were struck by lightning during the period. Most of the towers (78 per cent) were not struck more than twice during the eight-year period.

10. The maximum number of years in succession that any one tower has been hit is four, and this occurred only three times in eight years. Occasionally a tower is hit two years in succession, but it does not occur often.

11. It may be inferred from the extensive stroke data that the installation of localized lightning protection usually cannot be justified on the basis of a one- or two-year trouble record. The chances are that lightning will not strike the particular location in the years immediately following.

12. Three lightning currents ranging from 3,000 to 45,000 amperes have been recorded on a flagpole. The pole is about 300 feet above street level, and is the highest point within three city blocks.

13. From 104 sets of records obtained from towers with surge-crest-ammeter brackets on all four legs, it is possible to estimate the range in which a tower current lies when only one bracket record is available from a tower. When the single-leg records indicated tower currents of 2,000 amperes or less, the sum of the four leg records was as large as 50 times the single-leg indication. In the range from 2,000 to 70,000 amperes in a tower, the single-leg records usually were not very much in error. In the four cases where the tower current indicated by a single bracket was 76,000 amperes or greater, the sum of the four bracket readings was appreciably less than the single-bracket indication.

14. There were 25 cases where the surge-crest-ammeter links on a single leg yielded no current record when there was current in the other legs. These records showed tower currents as great as 6,200 amperes when no record was obtained from one of the brackets on that tower.

15. From the four bracket installations it is estimated that 6.4 per cent more strokes were recorded by them than would have been recorded if only one bracket had been installed on those towers.

16. Bonding of adjacent transmission towers appears helpful in reducing footing resistance. It apparently does not cause any appreciable change in the number of disturbances affecting more than one of a group of neighboring towers.

17. Flashovers occurred on 66-kv towers having as many as eight continuous-counterpoise conductors. However, the eight-year record of the 132-kv line indicates that a multiple-counterpoise system has prevented flashovers when the ground resistance is ten ohms or less.

18. A single continuous counterpoise seems to provide good protection for 220-kv towers having an insulator flashover level of 1,600 kv or more, provided that this type of grounding brings the footing resistances to less than the flashover value of the insulation in kilovolts divided by 100.

19. The average value of the surge impedance of a conductor in air seems to be less than 235 ohms. This is appreciably less than the theoretical value of 400 or 500 ohms often used. The data on which this estimate is based imply that mid-span clearances on transmission lines may not need to be so great as often are allowed for the prevention of mid-span flashovers.

20. Fairly good predictions of line performance can be made by a relatively simple empirical method.

21. The efficiency of protection of the 220-kv lines is estimated to be about 99.9 per cent. This high efficiency means that strokes causing flashover are so rare that many years may elapse between flashovers. The lowest efficiency of protection exists on one of the 66-kv lines, where it is about 97.5 per cent.

22. It is evident that preventive protection can be made very effective, but it does not attain perfection.

23. The largest recorded current through a lightning arrester was 7,400 amperes occurring in a 66-kv bank. A surge current of 9,700 amperes through a 220-kv expulsion protective gap was recorded.

Table XIV. Estimate of Lightning Outages on Line Section With Overhead Ground Wire

Ranges of Tower-Footing Resistance	Towers in Range		Maximum Safe Current for Towers in Range	Percentage of Tower Currents Exceeding Safe Values	Probability of Flashover
	Number	Per Cent			
0–1	3	8.83	680,000	0	0
1–25	0	0			
26–30	3	8.83	22,700	25	0.022
31–35	2	5.88	19,400	27.5	0.016
36–40	3	8.83	17,000	29	0.026
41–45	5	14.70	15,100	32	0.047
46	1	2.94	14,800	32	0.009
52	1	2.94	13,100	35	0.010
59	1	2.94	11,500	40	0.012
61–65	2	5.88	10,500	45	0.026
66	1	2.94	10,300	46	0.014
75	1	2.94	9,100	60	0.018
81–90	3	8.83	7,600	70	0.062
91–100	0	0			
101–110	2	5.88	6,200	78	0.046
114	1	2.94	6,000	80	0.024
120–125	2	5.88	5,400	82	0.048
151	1	2.94	4,500	86	0.025
305	1	2.94	2,200	95	0.028
355	1	2.94	1,900	97	0.029
Totals	34	100.00			0.46

Appendix. Estimating the Lightning Outages of a Transmission Line

Even a cursory survey of the literature on lightning protection indicates that a large number of factors should be considered theoretically when attempting to predeter-

mine the lightning performance of a line. Some of these factors are:

1. Number of storms per 100 miles, per year
   (*a*) Number of strokes.
   (*b*) Intensity of individual strokes.
2. Topography.
3. Cloud height.
4. Effective ground plane.
5. Soil resistivity and its variations.
6. Insulation.
7. Coupling factor.
8. Span length.
9. Mid-span clearance between conductors and overhead ground wires.
10. Shielding
    (*a*) Number of overhead ground wires.
    (*b*) Location of ground wires.
    (*c*) Influence of hillsides.
    (*d*) Nearby structures.
11. Surge impedances
    (*a*) Tower.
    (*b*) Overhead ground wires.
    (*c*) Grounding system.
12. Effect of method used in measuring ground resistance.
13. Area covered by grounding system.
14. Number and type of grounding electrodes.
15. Lightning current measurements
    (*a*) Accuracy of magnetic links.
    (*b*) Distribution of current in tower.
16. Wave shape of lightning surge.
17. Movement of conductors by wind
    (*a*) Effect on shielding.
    (*b*) Effect on clearances.
18. Design features affecting electrostatic field around insulation.
19. Effect of weather conditions on electrostatic field around insulation.
20. Instantaneous value of power voltage at instant of stroke.

Since inclusion of any large number of these factors in a computation is impractical, a method[4] was developed a few years ago which included only those factors that experience had shown to be most important. Initially the method was applied only to shielded lines, but now it is extended to all lines.

Experience with line *D* before its improvement with shielding and counterpoise afforded an opportunity to test the accuracy of the computations.

Before improvement, the line had a single overhead ground wire installed on end sections only. The computation of estimated flashovers resolved itself into three parts, one for each of the three types of line sections:

1. Overhead ground-wire section.
2. Towers.
3. Spans between towers without overhead ground wires.

Detailed Calculations

1. At the two ends of the line, there was a total of 4.25 miles of single overhead ground wire. This wire is assumed to provide practically perfect shielding for purposes of calculation. There were 34 towers in the sections having shielding wire. The footing resistances of these towers were distributed as indicated in Table XIV. The line insulation had a flashover level of about 510 kv. The coupling factor between the overhead ground wire and the conductors was about 0.25. The maximum tower potential without flashover is then safe tower potential = 510/(1 − 0.25) = 680 kv.

In Table XIV, the maximum safe tower current is obtained for column 4 by dividing 680 kv by the maximum footing resistance in each range from column 1. From Figure 2 is entered in column 5 the percentage of tower currents that can be expected to exceed the given maximum safe value. The probability of outage per stroke for each range of tower-footing resistance is the product of the values in columns 3 and 5 expressed as decimals. The total probability of outage per stroke for the section is 0.46. Since the average strokes per 100 miles of line per year for the entire transmission system is 113 (Table II), the probable outages per year for the overhead ground-wire section is 113(4.25 miles/100 miles) 0.46 = 2.2.

2. The section of the line without overhead ground wires was 18.58 miles long, which experienced (113 × 18.58)/100 = 21 strokes per year. The absence of the overhead ground wire made the coupling factor equal zero and the safe tower potential equal the flashover value of the insulation, which was 510 kv.

It is assumed[5] that 20 per cent of the strokes to the line hit the towers and the remaining 80 per cent hit the line conductors. The strokes terminating on the towers are assumed to cause flashover in accordance with probability calculations similar to those made for the overhead ground-wire section. The probable flashovers per year caused by strokes to towers without overhead ground wires come to 3.3.

3. There was an average of about 0.80 × 21 = 16.8 strokes each year terminating on line conductors between towers. It has been shown in the paper that the surge impedance of a conductor in air averages less than 235 ohms. On this basis, it can be assumed that the conductors on line *D* could carry more than 510 kv/235 ohms = 2,100 amperes, without flashover. From Figure 2 it is roughly estimated that ten per cent of the strokes to line conductors did not cause flashover. Accordingly, about 90 per cent of the 16.8 strokes that hit the line conductors each year caused flashovers, or 15.1.

A summary of the estimated flashovers on the three types of line sections is as follows:

Towers with overhead ground wires	2.2
Towers without overhead ground wires	3.3
Spans without overhead ground wires	15.1
Estimated tripouts per year	20.6

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Supervisory Control for the World's Most Modern Steel Mill

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WARTIME EXPANSION of the Pacific Coast shipbuilding industry has accentuated the need for new steel-producing facilities in the West. Moreover, rich deposits of iron ore, coal, and limestone—the raw materials required to produce steel—are close at hand in the central inland section of the western states.

To meet this need and to take full advantage of raw materials so strategically situated, a completely integrated steel plant has been constructed in that region. In this plant, the largest west of the Mississippi River, approximately 700,000 tons of finished ship plates and 200,000 tons of structural steel will be produced annually for Pacific Coast industry. This production goal required the building of 252 coke ovens, three blast furnaces, nine open-hearth furnaces, a 45-inch slab mill, a 132-inch plate mill, and a 28-inch structural-steel mill. Supplementary units include a sintering plant for treatment of the ore and an exceptionally large central maintenance shop. Adequate outside shop facilities are not available in the region of the plant, thus necessitating self-sufficient shop facilities within the plant.

For the first time in the history of steel-mill design, the entire electric-power supply and distribution system will be under the supervision and control of a centrally located power dispatcher. Particularly significant is the fact that all apparatus in the mill motor rooms likewise will be remotely controlled and unattended.

One of the most comprehensive supervisory control systems yet constructed will permit control of all of the widespread units of this plant from one dispatching center. This is in distinct contrast to the previous practice of maintaining local operators at all substations and local attendants in all mill motor rooms.

Supervisory control is a selective code system designed to provide remote control and supervision of a relatively large number of apparatus units through the medium of a single pair of control wires for each remote station. This system utilizes telephone-type relays throughout, and operates from a battery source of 48 volts direct current. It is simply a means by which remote-station apparatus can be supervised and directed, just as a substation operator is directed by telephone.

General

In designing the electric-power system for a new plant, the steel-mill engineer faces the same problems of generation, transmission, and distribution that confront the central-station engineer. However, in the utilization of this power for the production and processing of steel he is in a field peculiarly his own.

Of utmost importance is the problem of supplying 700 volts direct current for the main drive motors in the slab, plate, and structural-steel mills. Large motor-generator sets are required for this purpose, together with their associated exciter sets, ventilation equipment, and miscellaneous auxiliary apparatus. Particular interest, therefore, is centered in this mill motor-room apparatus and its special control and supervision features.

Up to this time it has been customary practice to provide an attendant in each mill motor room. His function is to control locally all motor-room apparatus. His duties include switching of all primary and secondary distribution circuits for the mill, as well as starting and stopping of all motor-generator sets and associated apparatus. An idea of the labor and time that would be involved in carrying out these duties in this new mill may be gained from the fact that the plate-mill motor room is 65 by 575 feet in area.

The single-line diagram (Figure 4) indicates the magnitude of the power system, which serves a plant area approximately $2^1/_2$ miles long by one mile wide. Although not shown, a large number of radial feeders are supplied from the distribution busses indicated for each substation.

Each unit of the project is provided with an entirely independent supervisory-control setup. These units are the open hearth, sintering plant, blast furnace, shop, coke plant, 138-kv tie substation, and the slab, plate, and structural-steel mills. Although all dispatching-office equipments are located at a common point, operations can be performed, or signals received over all equipments independently.

In this application, the electrical dispatcher is also the power-station switchboard operator. The dispatching-office supervisory-control equipment for each unit of the mill is incorporated in the same cubicle which houses the direct-acting control, as well as the metering and protective relaying, for the 13.8-kv feeder circuit supplying that unit.

With the power-supply system for the mills literally at the fingertips of the dispatcher, all motor-room apparatus can be placed in service with an absolute minimum of man power and in a minimum of time. Supervisory control provides immediate notice to the dispatcher of the loss of any normal power source. Standby tie lines between substations and between motor rooms can be switched in with minimum interruption to plant production. Provision is made also for the dispatcher to control system power factor in order to maintain maximum operating efficiency.

Completely automatic control of such motor-room apparatus as motor-generator sets and mercury-arc rectifiers has been available to the industry for many years and has proved itself in service. Coordination of such local automatic control with remote supervisory control makes possible an operating setup based on completely unattended motor rooms. Under normal operating conditions these motor rooms will be locked, and the apparatus therein will be accessible to authorized maintenance personnel only. Likewise, all conventional substation apparatus throughout the project will be unattended and locked in a similar manner.

As in previous mill practice, operators in control pulpits overlooking the slab, plate, and structural-steel mills will control locally all operations involving the handling of steel. With all motor-room apparatus ready to serve the mill, the pulpit operator will receive automatically a visual go-ahead signal, and, through the interlocking of a permissive relay, may proceed with mill operation.

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In the dispatching office, one or more panels are assigned to each station or mill unit under remote control. The control escutcheons are physically laid out in a logical arrangement with a miniature bus system in distinctive colors to indicate all principal busses, feeders, and tie lines. Each escutcheon is a small shield or panel which has assembled on it all of the control keys, push buttons, and indicating lights associated with a given apparatus unit.

Each dispatching equipment incorporates a station-alarm lamp, a pilot or "normal" lamp, and a control-line supervision lamp. The pilot lamp is the only one of the three normally lighted. This indicates that the system is at rest but in a condition to operate. Should a fault occur the alarm bell rings, and a station lamp shows the station from which the signal is coming. A glance at the group of escutcheons locates the individual breaker or protective device which has caused the alarm through the glowing of the disagreement lamp. Thus the dispatcher is able to note quickly what has happened and to restore service by reclosing the necessary breakers.

In this plant, there are 11 control centers and approximately 500 control points, with provision for an additional 200 future control points. In general, all 138-kv, 13.8-kv, 6.9-kv, 2.3-kv, and 460-volt 60-cycle circuits, as well as the 250-volt d-c circuits, are controlled by the supervisory-control system. All 13.8-kv circuits in the switchhouse, coke plant, sintering plant, and slab mill are equipped with breakers of 1,000,000 kva interrupting capacity. These are of the air-blast air-operated station type. Elsewhere, feeder reactors permit the use of 500,000-kva interrupting-capacity removable-type breakers. The 250-volt d-c circuits throughout the plant are supplied from ignitron-type rectifiers with semihigh-speed heavy-duty steel-mill-type circuit interrupters.

Figure 1. A short section of the dispatching control board

Details of Operation

As previously noted, the supervisory-control equipment operates from 24-cell battery circuits. The use of alternating current is undesirable since the control system, which brings vital information to dispatching headquarters during times of trouble, is most important when the a-c supply is off. For each station under remote control only two telephone-type line wires are required.

The selecting system consists of straight counting codes. In case of a selection initiated by the dispatcher, the desired code is sent to the remote station, where the selected relay returns its code to the office. If the returned code does not agree with that sent out, no further operation is possible. If it does agree, the "check" or point lamp on the individual escutcheon is lighted. For a circuit-breaker operation the dispatcher then turns the twist key to the desired "close" or "trip" position and presses the master-control push button. This action sends the closing or tripping code to the selected unit, causing it to operate. As the breaker changes position, an auxiliary switch causes the new position to be reported to the dispatcher, changing the red and green lamps to correspond.

An automatic operation is reported in a similar fashion. Should a circuit breaker trip automatically, its auxiliary switch causes its selecting code to be transmitted to the office and the alarm bell to notify the dispatcher that some action is required. The office relay returns the check code to the substation, which immediately sends its position code to change the red lamp indication to green. As the dispatcher hears the bell, a glance at his row of panels informs him which substation is involved by the lighting of a station-selection lamp. On the panel reporting the alarm the individual breaker that opened is clearly indicated by the disagreement lamp. The dispatcher may select and reclose the breaker immediately. Should a permanent fault cause the breaker to reopen immediately, he may dispatch his maintenance crew to locate and correct the fault.

Once each week it may be desirable to test the over-all supervising system. The accepted method consists of a "master check," in which the dispatcher presses a master-check push button. This causes a checking code to be transmitted to the remote-control center, which compels each circuit breaker or other operated device to send its present position code to the dispatcher's board. Thus the equipment is given an over-all positive test and, at the same time, assures the dispatcher that all equipment is in good working order.

If automatic-breaker operations occur at the substation during the master-check operation they will be indicated immediately, provided that the master check has progressed beyond their point-assignment number. Otherwise, they will take their proper turn in the point-assignment sequence.

If it should become necessary for the

dispatcher to select and operate any substation device during master check, he may do so. The only special requirement is that he hold the selection key in the depressed position until the point-selection lamp is lighted.

As soon as the desired operation on that point is completed, the master-check operation will be resumed automatically. At the end of the master-check operation the alarm bell will be energized to notify the dispatcher that the check has been completed; he must then depress the "reset" key to silence the alarm.

In periodic testing or for special operations following maintenance work, it is sometimes desirable to operate a breaker several times. In order to save time and eliminate the necessity of reselection, the selection may be retained by holding the master-control push button in the closed position until the red and green indicating lamps have changed position indication. In this way the selection is maintained and, by changing the position of the twist key to the opposite position and again pressing the master-control key, the opposite operation is performed. On the last operation, if the master-control push button is not held in too long, the equipment will reset automatically and become available for any other desired operation.

The supervisory-control equipment is composed of extremely simple, mechanically uniform telephone relays, which send and receive codes at approximately 14 impulses per second. No polarized relays or selector switches are used. The control is fast, positive, and inherently antipumping, and automatically checks each selection. The entire equipment normally is at rest. Continuous individual lamp indications are provided for supervising the position of each remote apparatus unit.

Control by the dispatcher is performed in a manner very similar to that in which an operator in the remote station itself would control the apparatus by means of the usual local control. Coded operation control provides protection against the possibility of false operation of any apparatus unit due to foreign voltages on the line wires that might be caused by surges from nearby power lines or lightning.

Transfer Switches

At all remote locations any apparatus unit can be transferred at any time from remote to local control by means of local transfer switches. Remote supervision of the positions of these transfer switches is provided by voltage groups. In addition, each group of transfer switches also controls a corresponding indicating lamp installed over the substation or motor-room door. This lamp is lighted when any one of the group of transfer switches is turned to the local-control position. Thus it serves as a warning to a maintenance or test engineer about to leave the station, should he unintentionally leave one or more transfer switches in the local-control position. As a safety precaution, any apparatus unit may be tripped by local control at any time, regardless of the position of its transfer switch. The dispatcher retains supervision of positions of all apparatus units, even though they may be under local control.

Control Lines

Each pair of control lines is supervised continuously to detect open-circuit or short-circuit conditions. Each such channel is used also for telephone communication with its associated station, without interfering with supervisory-control operations. This communication feature permits the dispatcher to keep in contact with maintenance men at any station.

Should a short circuit or an open circuit develop in a control line, the alarm will sound, the "normal" lamp will be de-energized, and the line-supervision lamp will be lighted. Depressing the "reset" key will silence the alarm, but the "normal" lamp will remain de-energized and the line-supervision lamp will remain lighted until the line trouble is corrected and the "reset" key is depressed again.

If any substation-apparatus units have changed position during this time, the alarm will sound again as the "reset" key is depressed, and all changes then will be so indicated automatically and in numerical sequence.

Supervisory Versus Direct-Wire Control

Although the distances between the dispatching office and the remote-control stations are relatively short, the large number of operations required at each station fully justifies the supervisory-control system. The use of a single pair

Figure 2. Dispatching-office supervisory-control cubicle, with open doors showing flush-mounted relay cases on inside panel

of wires to each remote station, as contrasted with direct-wire control, represents a major saving in copper that is so essential in today's conservation program.

The use of supervisory control has many operating advantages over any direct-wire control scheme. Supervisory control requires a minimum of space and readily accommodates future additions. Line troubles are reduced to a minimum, and the line wires are supervised continuously for open circuits and short circuits. Protection from induced voltages, or contact with power lines, is simpler to provide than with direct-wire control. Supervisory control also accommodates voice communication.

Motor-Room Control

Each mill motor-room has an oil cellar in which are located the various oil pumping systems for the bearings of the rotating apparatus within the motor room. These oil cellars are accessible from the outside of the motor room, and will be under the care of an attendant.

Because of the need for heating of the lubricating oils under certain conditions and the intricacy of the system of valves required, it was not considered feasible to place the oil-cellar equipment under supervisory control.

No action will be taken toward starting of the motor-room equipment until the oil-cellar attendant reports all oiling systems ready for operation.

Preparatory to starting the main motor-generator sets, the dispatcher will disconnect all space heaters. These heaters prevent moisture condensation on the machine windings during shutdown. Next he will start all fans and auxiliary exciter sets.

He then will start the flywheel motor-generator set, which will accelerate automatically under slip-regulator control. After the unit reaches normal speed at no load, a relay is energized which notifies the dispatcher that the set is ready for mill operation. This relay also sets up a permissive circuit to the control pulpit in the mill and lights a lamp which indicates to the mill operator that the mill is ready for his control.

The synchronous motor-generator sets in the plate and structural-steel mills also are started by the dispatcher, and will accelerate under automatic control. Reactor starting is utilized for these sets. Having reached maximum speed with the reactor in circuit, the field is applied automatically to bring the motor up to synchronous speed. At this point the starting reactor automatically is short-circuited. Through an interlock on the field switch the dispatcher is notified that the set is up to speed.

In case protective devices indicate approaching trouble, such as overheated bearings, the pulpit operator may clear his rolls of steel before the affected power-supply units are shut down.

Local interlocking is provided in each mill motor room to insure against apparatus units being started in any but the proper sequence. A synchronous or flywheel motor-generator set cannot be started until its associated exciter sets are in operation. The flywheel set, which is equipped with a wound-rotor driving motor, cannot be started unless its liquid slip regulator is in the resistance-all-in position. Furthermore, dynamic braking of this same set cannot be applied unless the regulator is again in the resistance-all-in position and the motor primary breaker is open.

Figure 3. Typical supervisory-control relay and control-escutcheon assembly

Regulator Control for the Structural-Steel Mill

The synchronous motor-generator set for the structural mill is equipped with an automatic power-factor or reactive-kilovolt-ampere regulator, which can be cut into and out of service by supervisory control. A similar regulator is provided for the two synchronous motor-generator sets in the plate mill. The dispatcher is provided with supervision of the latter regulator; that is, he has indication of whether or not it is in service, but he cannot control it.

With all mills operating normally, the plate-mill synchronous motor-generator sets will be under automatic-regulator control. The structural-steel-mill regulator will be cut out of service, and the synchronous unit will operate at a fixed full-load excitation value.

When the plate-mill regulator is cut out of service (by manual control at the regulator), then the structural-steel-mill regulator should be cut into service. If the plate-mill synchronous units are operated without regulator control, their excitation also will be set at the full-load value.

No-Alarm Feature

To complete his picture of operating conditions in the mills, the dispatcher is provided with supervision but not control of certain apparatus units directly controlled by the mill operator. This group includes such units as the scale breaker, the spreader, the edger, and the d-c breakers on the flywheel and synchronous motor-generator sets.

These units may be started and stopped, or the d-c breakers closed and opened, frequently during normal mill operation. To avoid unnecessary annoyance to the dispatcher, the associated changes in supervisory-lamp indications are not accompanied by an audible alarm, as is the case on other supervision points.

Miscellaneous Supervision Features

Continuity of power supply to all busses in all stations is supervised continuously through the medium of bus-voltage relays. This feature indicates whether or not a given bus is energized, but does not indicate the actual bus voltage. Operation of any station annunciator is reported immediately by supervisory control.

Rectifier Control

In placing a rectifier in service by supervisory control, the dispatcher must first close the a-c breaker and then the positive and negative d-c breakers. Electrical interlocking is provided to prevent the reverse sequence of operation.

Shutdown of a rectifier may be accomplished by tripping the a-c breaker, which in turn will automatically trip the d-c breakers through electrical interlocking. If desired, the d-c breakers and then the a-c breaker may be tripped independently, in that sequence.

Closing and tripping of both the positive and negative d-c breakers for a given rectifier are combined on the same supervisory control point. Supervision of the

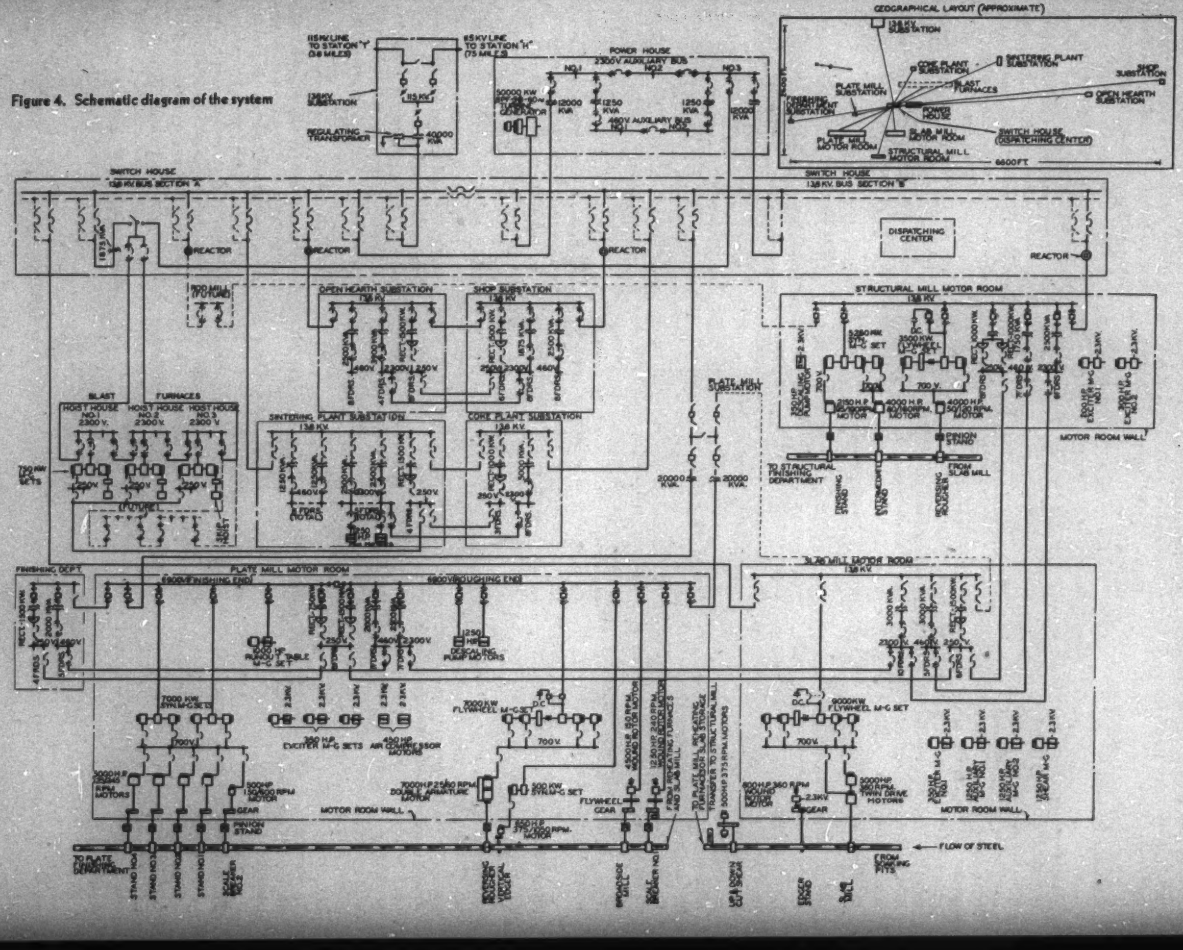

Figure 4. Schematic diagram of the system

position of each such pair of breakers is obtained through two interlock contacts in series (one on each breaker), to insure that both breakers are closed when so indicated.

Rectifier Protection

Causes of shutdown of rectifiers are segregated into two groups. If shutdown is due to a temporary condition such as overload or reverse current, the unit may be restored to service safely by the dispatcher as soon as the protective-relay equipment will permit. (A very heavy short-time overload will be detected by induction-type a-c overload relays, and a continuous overload condition of lower value by the thermal device on the rectifier transformer.) This type of shutdown will be indicated by tripping of the a-c and d-c breakers.

On the other hand, shutdown resulting from loss of the rectifier-cooling water supply or from excess temperature of a rectifier tank or mercury-vapor pump probably will necessitate the attention of the maintenance engineer. This type of shutdown will be indicated by operation of the rectifier annunciator alarm, as well as by tripping of the a-c and d-c breakers. Thus the dispatcher can determine his course of action accordingly.

Step-Regulator Control

Control of the step-type regulating transformer bank at the tie station to the utility company is also under the dispatcher. Tap position may be checked at any time, and is indicated simultaneously with control of the tap-changing mechanism. A local "on position" indicating lamp is provided at the substation to indicate that the regulator is on a definite tap position at any given time. The lamp indication is duplicated on the dispatcher's escutcheon for this regulator control.

Tie Substation Alarm Features

In recognition of the importance of the 40,000-kva transformer bank which serves as a tie between the utility power system and the mill, operation of all associated alarm devices is reported by supervisory control. Individual supervision is provided for pressure alarm, oil-level alarm, oil-temperature alarm, and an alarm upon starting of the blowers, by automatic control.

A similar alarm is given also for low air pressure in the supply system for the pneumatically operated 138-kv oil circuit breakers in the tie substation.

Pilot Channel Supervision

Pilot-wire relaying is utilized to protect the several sections of a loop-type power supply for the blast furnaces. The pilot-wire channel for each of these sections is supervised continuously by the type of auxiliary relays customarily used to detect short circuits, open circuits, and grounds. The alarm contacts of these relays operate through the supervisory-control system to warn the dispatcher, so that he may promptly institute corrective action if trouble should develop.

Door-Lock Supervision

All remote stations and mill motor rooms are normally unattended and the entrance doors are locked. The dispatcher is provided with continuous supervision of each of these door locks. A special contact is actuated by the door-lock mechanism, and is independent of the actual door position. Thus, once the door is unlocked, maintenance men may go in and out without actuating the alarm.

Maintenance men will be required to check in with the dispatcher by telephone when entering a remote station, and again when they are ready to leave. The door-lock supervision feature provides a final check to make certain the station door is left locked.

Blackout

Supervisory control also provides a vital wartime feature in that the dispatcher can institute a complete blackout on a moment's notice. In general, only external lighting will need to be switched off for this purpose, as all principal units of the project are of windowless construction.

Operative Burden

At first thought, the operation of such a system as this by a single dispatcher would appear to be placing too much burden on one operator. However, once the power system is in service, system changes will be relatively infrequent. Troubles will occur, as on any system, but they should be isolated in nature. Moreover, troubles at any point on the system can be recognized immediately and prompt corrective action taken.

Ample notice will be given when starting up any of the mills. Several hours' time normally is allowed in which to place in service all rotating apparatus in a given mill motor room preparatory to rolling steel.

Conclusion

Although such equipment is a comparative newcomer to the steel industry, supervisory control has served the central-station industry since 1921. The original installation is still in daily operation. Its basic soundness is well illustrated by the fact that the same type of relays and the same fundamental principles of circuit design are still in use today.

No part of the supervisory control for this plant is new in design. Furthermore, its application to switching operations in the substations throughout this project is entirely conventional. Only the application to motor-room motor-generator sets and associated apparatus is new.

Man-power shortage is particularly critical at this time in the field of technically trained and experienced steel-mill power-system operators. Thus an estimated 80 per cent saving in such man power for this project, effected by the use of centralized control, represents a vital contribution to the war effort.

Centralized control has required coordinated planning and uniform practices throughout the project. With so many engineering firms involved in the design and construction of the many mill units, this is a matter of utmost importance. As the most comprehensive system of supervisory control yet applied to a major steel mill, this installation will point the way for future installations within the steel industry.

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SAFE AND SIMPLE TERMINALS are one of the accomplishments made possible by **KERITE ENGINEERING** and the characteristics of Kerite insulation!

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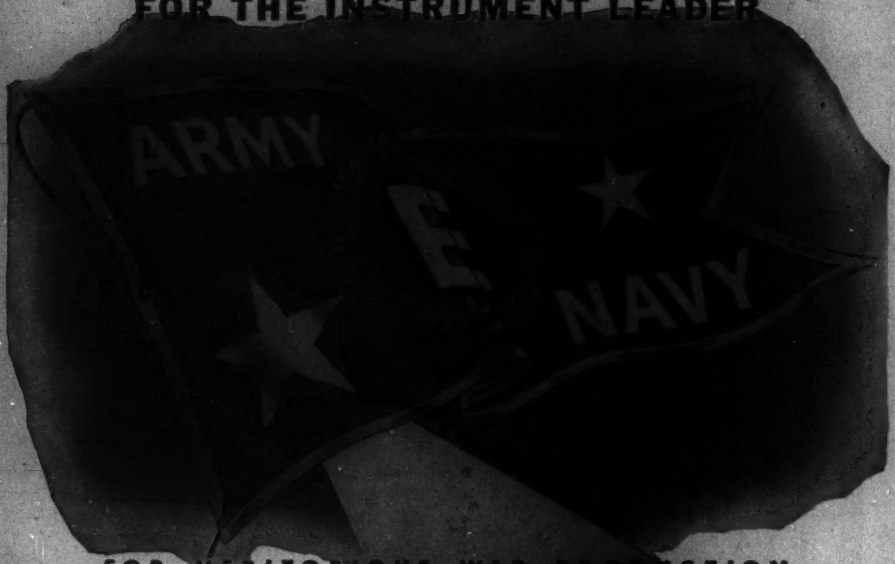

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This third citation for meritorious war production . . climaxing a long record of war service . . . is a source of justifiable pride to the men and women of WESTON.

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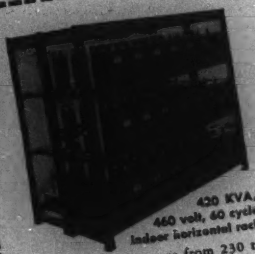

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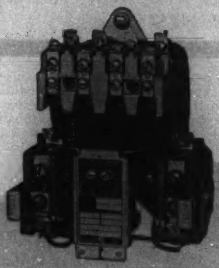


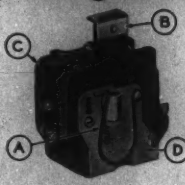
FOR SEPARATE MOUNTING— OR FRONT MOUNTING ON SIZE 0 AND 1 STARTERS

New Type AR Overload Relays provide an easy yet positive method of changing from automatic to hand reset. Adjustability of the tripping point affords greater accuracy of overload protection and flexibility of application. Terminals are large and easily accessible.

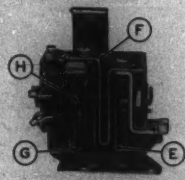
Automatic reset overload relays are useful whenever starters are mounted in remote or inaccessible locations. They are particularly well suited for built-in machine tool control because they eliminate costly external reset mechanisms. No extra charge is made for these automatic reset devices on starters or machine tool control panels.

For complete details call in your Square D Field Engineer or write for Bulletin 201, Industrial Controller Division, 4041 N. Richards Street, Milwaukee 12, Wisconsin.

AUTOMATIC RESET

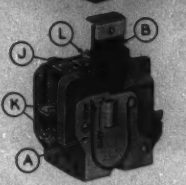


With spring wire clip (A) in hole marked "Auto" and reset slider (B) depressed, relay is in automatic reset position. Insulation blocks (C) are cold molded non-carbonizing material, wax impregnated to prevent absorption of moisture. Steel reinforcing plate (D) protects against breakage and serves as front mounting bracket.

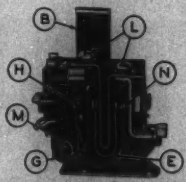


Floating bimetal trip element (E) is "U" shaped to fit around heater (F). This unusual design automatically compensates for any slight variation in shape or location of heater. Change in ambient temperature has little effect on the high temperature bimetal. With cam (G) in ◀ position, contacts will automatically reset after bimetal cools and releases tripping pin (H).

OR HAND RESET



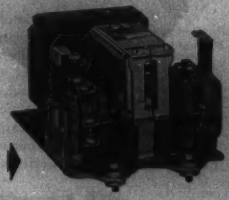
Moving spring wire clip (A) to hole marked "Hand" releases reset slider (B) and provides hand reset operation. Note husky size of load terminal (J) and control terminals (K). Heater units are firmly attached by screws (L) but are easily installed or removed from the front even after starter is mounted and wired.



With cam (G) in ▶ position, the contact mechanism goes overcenter when trip pin (H) is pushed as bimetal (E) expands with heat. Silver contact tips at (M) remain open until operation of reset slider (B) turns cam (G) to ◀. Mechanism is trip-free, thus the snap action contacts cannot be held closed against an overload. Note screw (N) which serves as stop for bimetal, also providing adjustment.

Simple means for adjustment of the trip point from 85% to 115% of nominal rating is a valuable and unique feature of this new Type AR overload relay. It permits changes in setting to take care of variations in ambient temperature or load conditions at the motor. In addition, overload protection is not limited to the usual selection of heater sizes since intermediate points can be obtained, easily and quickly.

Type AR relays are designed for maximum accessibility and ease of wiring. Photograph of starter shows how load terminals are out in front for easy wiring, while control terminals are at bottom, away from other parts. Thus, it is very easy to connect overload relays of several starters in series, or to wire additional relays in the circuit. Likewise, it is easy to convert a standard starter to 2 wire separate control.



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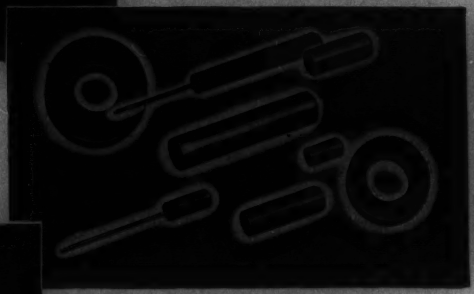

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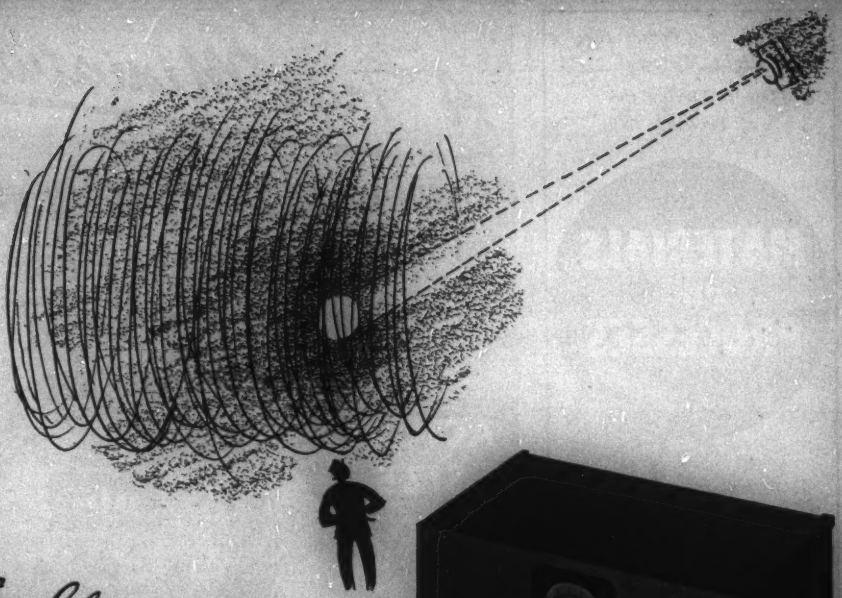

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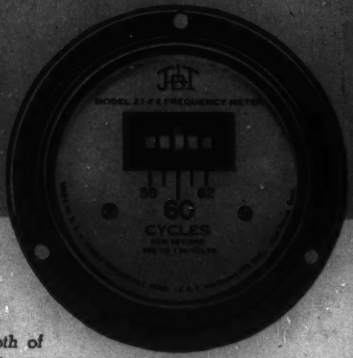

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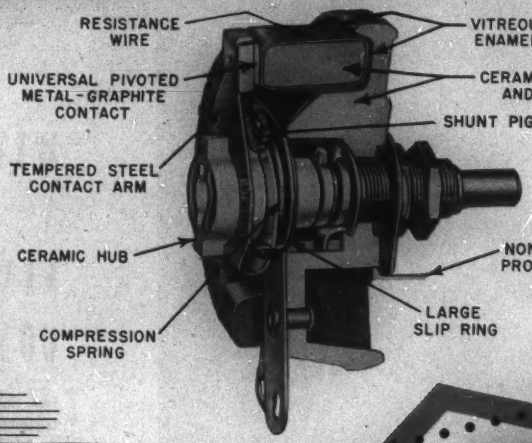

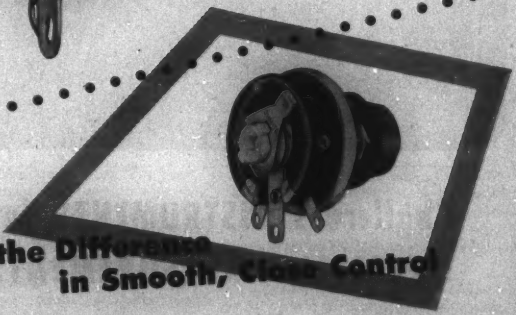

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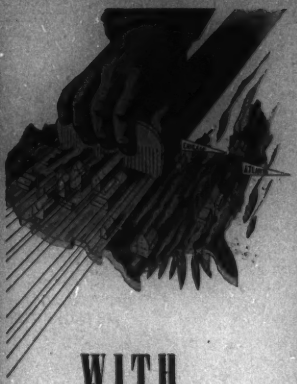
Kelvin-Wheatstone Bridges
Low-Resistance Test Sets
High-Voltage Measuring Apparatus
Special Telephone and Telegraph Instruments
. . . and many others

Whether for laboratory, school, production, or maintenance use, Shallcross offers an extensive line of electrical measuring apparatus, fully tested and proved through years of use under all conditions and in all parts of the world.

WRITE FOR CATALOG—or describe your requirements and our engineers will gladly make specific recommendations.

SHALLCROSS MFG. CO.
ENGINEERING • DESIGNING • MANUFACTURING
Dept. EE-54, Collingdale, Pa.



WITH A FINE COMB

Ever vigilant, Lafayette Radio Corporation's tracers fine-comb the field for radio and electronic components and equipment. We deal only with top-flight manufacturers, so quality and performance are assured. And the accent throughout is on Service. Wherever possible, same-day deliveries are maintained. If technical and priority problems perplex you—we've got 25 years of experience behind us to help pull you through. Call, write, wire, or teletype—either to Chicago or Atlanta. Orders, in any quantities, filled from both cities. Note: we build equipment to specifications.

Write or wire Dept. C-5 for our new 8 page circular listing merchandise available for immediate delivery. All of this material is subject to prior sale.

If you live in or near one of the 35 blood bank center cities, call the Red Cross today for an appointment . . . . . your blood is needed.

Lafayette Radio Corp.
901 W. Jackson Blvd. CHICAGO 7, ILLINOIS
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The LINK C-N-T synchronizes the operation of its maze of precision instruments with built-in CONSTANT VOLTAGE

The Link Crew Navigation Trainer will go down in history as one of the outstanding scientific contributions to early and complete victory in this war.

Firmly anchored to the ground where a mistake will not be costly in life and equipment, "freshmen" of the united nations' air forces learn the fundamentals of aerial warfare. Thus thousands of lives have been saved, hundreds of bombers released for duty at the front, and thousands of airmen go forth better equipped to master the problems of actual combat.

The Link C-N-T is a teamwork trainer for pilot, navigator, radio operator and bombardier. The heavens are accurately reproduced for celestial navigation. The pilot guides his ship over accurately duplicated terrain. The radio operator maintains communication with an airbase. The bombardier "lays his eggs" on the target. And all of these "long range" missions take place in a small, circular building only slightly larger than the familiar silo on our dairy farms.

The results of this careful, safe training have been "more bombs on the targets—more planes and crews safely home."

In order to maintain accurate coordination in all of these various functions a specific operating voltage had to be maintained. Due to the heavy power loads, available voltages were fluctuating over such a wide range that accurate operation of the C-N-T was difficult.

The answer was built-in SOLA Constant Voltage Transformers which, regardless of power line fluctuation, duplicated the operating voltage called for on the label.

Here is another typical example of improved product design made possible by automatic, self-protecting SOLA Constant Voltage Transformers. Available in standard units from 10VA to 15KVA or custom built to design specifications.

SOLA
Constant Voltage Transformers

To Manufacturers:
Built-in voltage control guarantees the voltage called for on your label. Consult our engineers on details of design specifications.

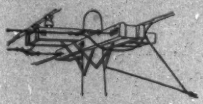
Ask for Bulletin ACV-74

Transformers for: Constant Voltage • Cold Cathode Lighting • Mercury Lamps • Series Lighting • Fluorescent Lighting • X-Ray Equipment • Luminous Tube Signs Oil Burner Ignition • Radio • Power • Controls • Signal Systems • Door Bells and Chimes • etc. SOLA ELECTRIC CO., 2525 Clybourn Ave., Chicago 14, Ill.

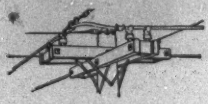
SAVE $5.00 A TURN OR DEADEND

on 000 to 1,500,000 C.M. cable with

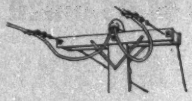
Matthews Cable Clamps



Shows how strain caused by right angle taps can be relieved



Outside Turns, Straight Guys



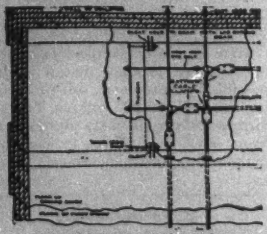
Deadending Two Cables

Order Number 2 for use on D.C. Cable or Number 3 for use on A.C. Cable.

Hundreds of thousands of these Clamps have been sold.

Every order for 000 to 1,500,000 C.M. Cable should include an order for Matthews Cable Clamps for every corner or deadend.

Write for Bulletin C.



Right Hand Turns in Heavy Cable

W. N. MATTHEWS CORPORATION

ST. LOUIS, U. S. A.

Although "Megger" testing instruments are sometimes referred to as "Meggers," there is actually no such thing as "a Megger." Why? Because the name "Megger" is a trade mark which is registered in the U. S. Patent Office and it applies in this country *only* to certain electrical instruments that are sold exclusively by the James G. Biddle Company. • These facts are re-stated here to prevent misunderstandings that may arise from careless or misleading use of the term "Megger." • The more widely used of these "Megger" instruments are listed below. Full information will be furnished on inquiry.

"Megger" Insulation Testers	*Bulletin 1735-EE*
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EXTRA DIVIDEND ON A SOUND DECISION

"WE DIDN'T EXPECT A WAR
WHEN WE STANDARDIZED
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In normal times, the "regular dividend" on Copperweld guy strand is non-rusting long life. In these wartimes, Copperweld pays an "extra dividend," saving manpower and materials, by eliminating costly replacements of rusted guys.

The strong steel core of Copperweld strand is protected from rust by the thick exterior of copper inseparably molten-welded to the steel. You "guy for the life of the line" with Copperweld's copper-protected strength.

Plan to get the performance qualities that *only* Copperweld can give you. Our representatives throughout the country are at your service. Call upon them for further assistance and information.

Copperweld Steel Company · GLASSPORT, PA.

Eimac Vacuum Pump

To create the nearly perfect vacuum within Eimac tubes and put vacuum pumping on a mass production basis, Eimac Engineers developed a whole new vacuum technique and much special equipment.

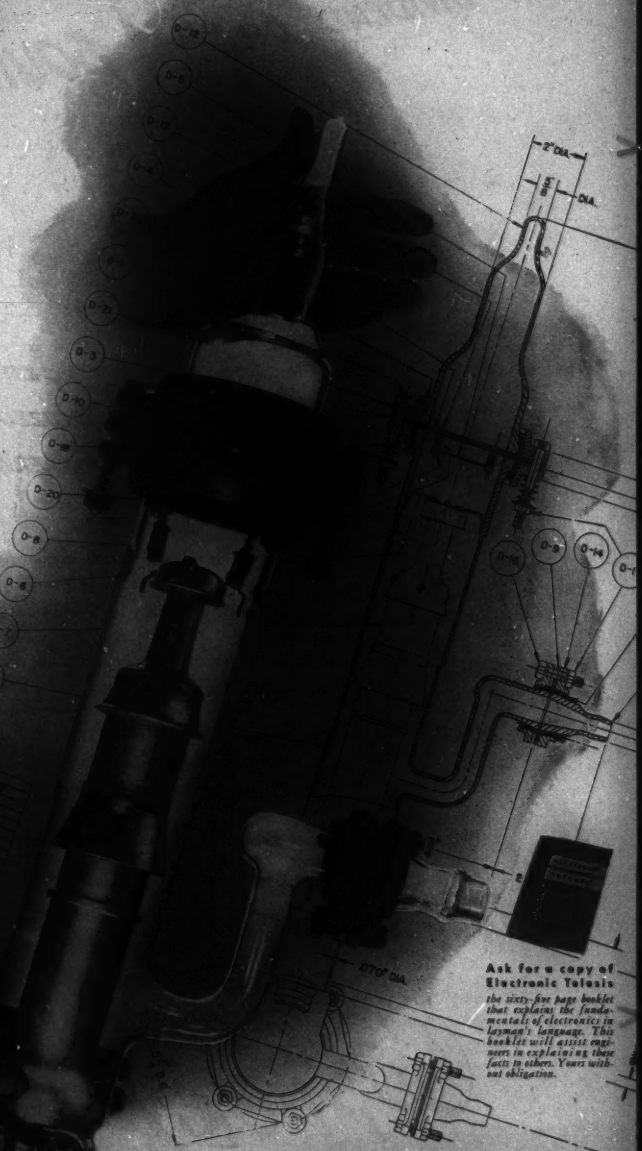
One of the devices resulting from these years of research and development is the Eimac HV-1 Diffusion Pump together with the special vaporizing oil which it requires.

Today this pump is being made available to manufacturers and research laboratories throughout the world. You can obtain full information and technical data without cost or obligation by writing direct to the San Bruno plant address below.

This Eimac HV-1 pump is one good reason why Eimac tubes are unconditionally guaranteed against premature failures which are caused by gas released internally. This reason plus outstanding performance, great stamina and others have made Eimac tubes first choice of leading Engineers throughout the world.

Follow the leaders to

Eimac TUBES



Ask for a copy of Electronic Talesis

the sixty-five page booklet that explains the fundamentals of electronics in layman's language. This booklet will assist engineers in explaining these facts to others. Yours without obligation.

EITEL-McCULLOUGH, INC., 816 San Mateo Avenue, SAN BRUNO, CALIFORNIA
Plants located at: San Bruno, California and Salt Lake City, Utah

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IRC WILL BE RE

with TYPE BW INSULATED WIRE WOUND RESISTORS

At the first indication of lessened demand by the Armed Services, IRC will be in an excellent position to immediately supply industry's requirements for resistors of *all* types. That IRC units will be available in ample quantities on a favorable price basis is assured because we have developed and are operating on a mass production basis the world's largest resistor plants.

RESISTOR PROBLEMS WELCOME

Feel free at all times to consult with us on your peacetime product design plans involving resistances. You can be certain of unbiased engineering counsel and secure in the knowledge that the subject matter will be held inviolate.

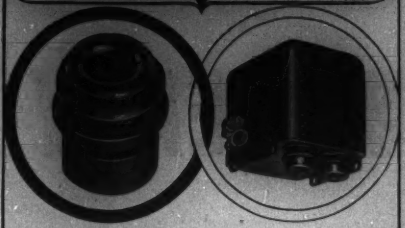
CHECK THESE FEATURES OF TYPE BW WIRE WOUND RESISTORS

1. *Completely insulated wire wound of standard ½, 1 and 2 watt sizes.*
2. *Resistance values: ½ watt—from .24 ohms to 800 ohms; 1 watt—from .5 ohms to 5000 ohms; 2 watt—from 1.0 ohms to 8000 ohms.*
3. *Have wire wound stability and are physically interchangeable with carbon types.*
4. *Available in matched pairs to 1% or 2% for close-tolerance, high-stability applications.*
5. *Element is space wound with copper-nickel or nichrome bare wire securely crimped and molded integrally with leads.*

PREFERRED FOR PERFORMANCE · IRC · FIXED RESISTORS

INTERNATIONAL RESISTANCE CO.

THIS UNIVERSAL INSULATOR
Helps Maintain
DONGAN *Dependability*



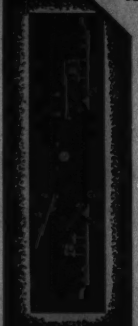
This Dongan Oil Burner Ignition Transformer has earned a reputation for dependable performance. It's designed right and constructed right—down to the last detail. And one of these important details is Universal bushings. Universal genuine porcelain "made to order" insulators have high dielectric strength; withstand thermal shock and arcing; are non-corrosive; resist acids; and will not carbonize because they contain no organic binders.

If you're re-designing for post war as well as for current production—better investigate the advantages of Universal porcelain insulators.

THE UNIVERSAL CLAY PRODUCTS CO.
1560 EAST FIRST ST. • SANDUSKY, OHIO

AUTOMATIC TRANSFER SWITCHES

ASCO Electrically Operated TWITCHES



Showing actuating double throw inter-locked mechanical construction

Sure in Their Work!

Check these ASCO operating features carefully.

1 . . . contact arms inherently interlocked both electrically and mechanically because of double throw design

2 . . . actual double throw construction

3 . . . no neutral position possible due to coil or control failure

4 . . . coil energizing power comes from selected source only

5 . . . contacts cannot weld closed

These and other ASCO features mean positive action. They mean that the load will get service if either power source is okay. . . . The same dependability is built into ASCO Remote Control Switches, Relays and Contactors.

. . . . . .

We also make a complete line of Solenoid Operated Valves for controlling the flow of liquids and gases.

Automatic Switch Co.
41-H EAST 11th STREET, NEW YORK 3, N. Y.
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Savings in DESIGN

UTC engineering is well demonstrated in these photos which illustrate a contemporary transformer brought to us for duplication and (below) UTC final design.

TYPICAL IMPROVEMENTS:
VOLUME REDUCTION 80%
WEIGHT REDUCTION 78%
PRICE REDUCTION 84%
DEPENDABILITY PLUS — 9% now submersion proof

May we design a war unit to your application?

UNITED TRANSFORMER CO.
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"DIE-LESS" DUPLICATING
SAVES MAN HOURS AND DELAYS
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A non-profit research laboratory engaged in urgent war research must increase its scientific staff. MEN OR WOMEN (COLLEGE GRADUATES), with experience in vacuum tube circuit design, construction of aircraft radio equipment and design of small electro-mechanical devices are needed.

Salaries range from $3,000 to $8,000, depending upon experience, ability, education and past earnings.

Release statement and USES consent needed.

Apply by mail.

AIRBORNE INSTRUMENTS LABORATORY
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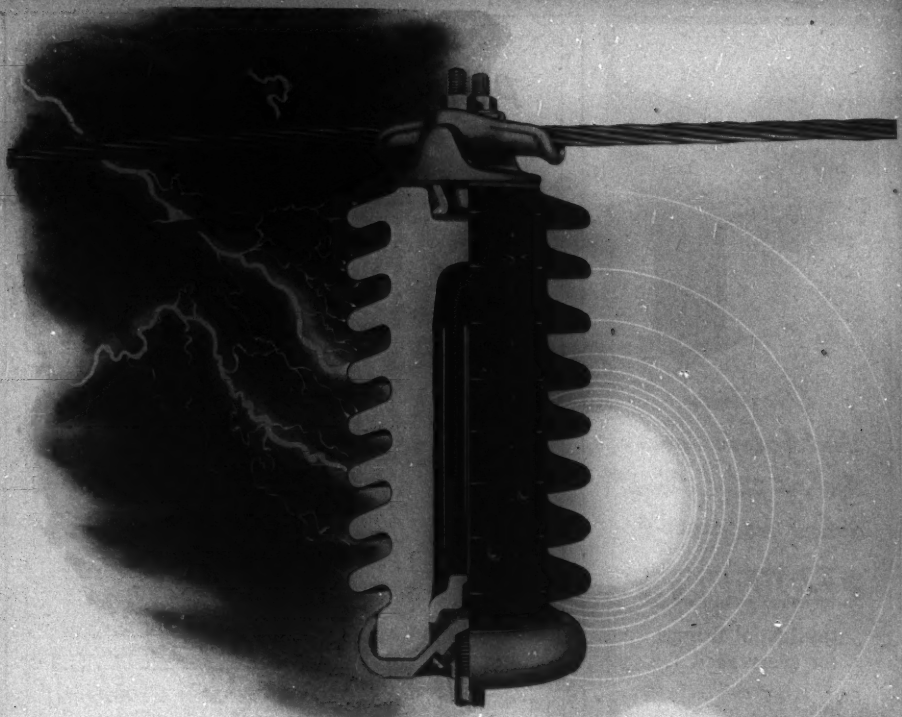

You'll never see what makes an O-B line post work

In line post design, the *inside* is more important than the outside. The inner chamber must be totally dry--always! A moist surface here would cut out an important amount of insulation and place a hazardous electrical stress on the porcelain head. A steep front lightning flash can be fatal under these conditions.

Thermal cycles produce alternate pressures and vacuums in this closed chamber. Moisture does not tend to seep in--it's drawn in, if the seal is not perfect, even after years of exposure.

O-B line posts have this chamber sealed off with a porcelain barrier, glazed into place. Nothing is any more secure or more permanent. The inert dry gas which fills the chamber stays dry and, in turn, the insulator retains its original excellent electrical qualities indefinitely, despite climatic conditions.

If you favor the line post in your construction, be sure to specify O-B and get the ceramic seal to assure longest trouble-free service.

BACK THE ATTACK
BUY MORE WAR BONDS

Ohio Brass

MANSFIELD, OHIO

CANADIAN OHIO BRASS COMPANY, LIMITED,
NIAGARA FALLS, ONTARIO

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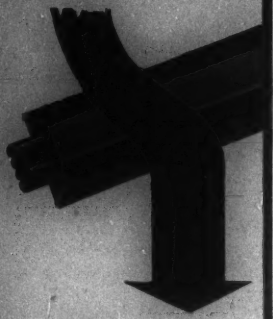
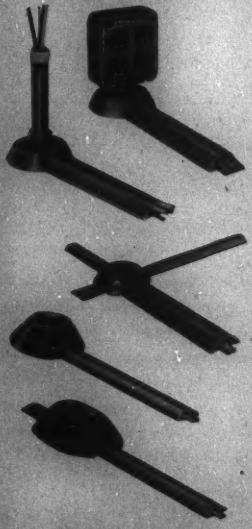


You may Safely wire on top of the floor where necessary

FLORDUCT

substantial fittings for every need . . .



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PRODUCTS CORPORATION
Pittsburgh, Pa.

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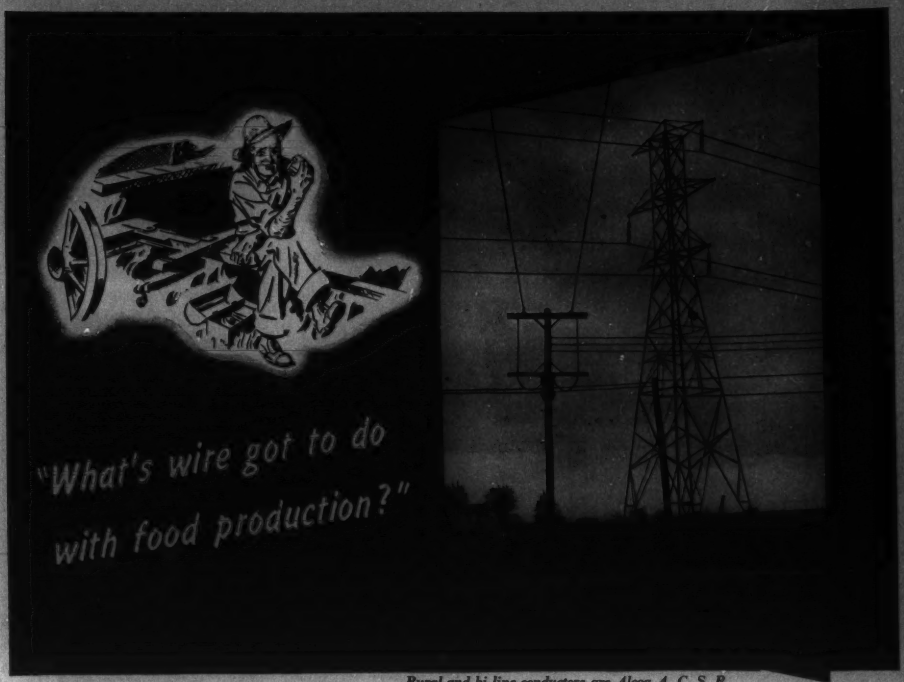
which they desire to introduce to the British Market, are invited to send particulars of their products to—
THE ELECTRICAL APPARATUS CO. LTD.
ST. ALBANS, ENGLAND



Rural and hi-line conductors are Alcoa A. C. S. R.

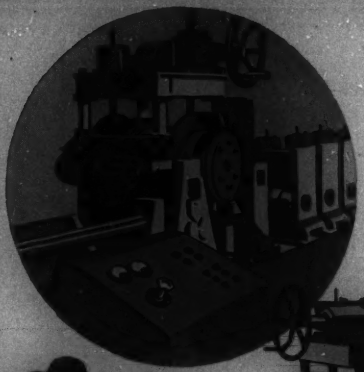
The electricity flowing in those two lines is headed in different directions. To the city, where it drives machines that fabricate the equipment our fighting men must have. To the country, where it helps the farmer produce the foodstuffs the whole world is needing. Both are vital war production.

Recognizing that rural lines and hi-lines, alike, must be kept working at top efficiency, power conductors and fittings were long ago made available for emergency work.

If you're planning to extend existing lines, install conductors of sufficient size to deliver *all* the power that's needed. Otherwise you handicap the man who is counting on using electricity to replace workers who have gone to war. A.C.S.R. provides the desired combination of high electrical conductivity, high strength and resistance to corrosion.

Alcoa engineers will gladly assist on your line maintenance and construction problems. ALUMINUM COMPANY OF AMERICA, 2149 Gulf Building, Pittsburgh 19, Pennsylvania.

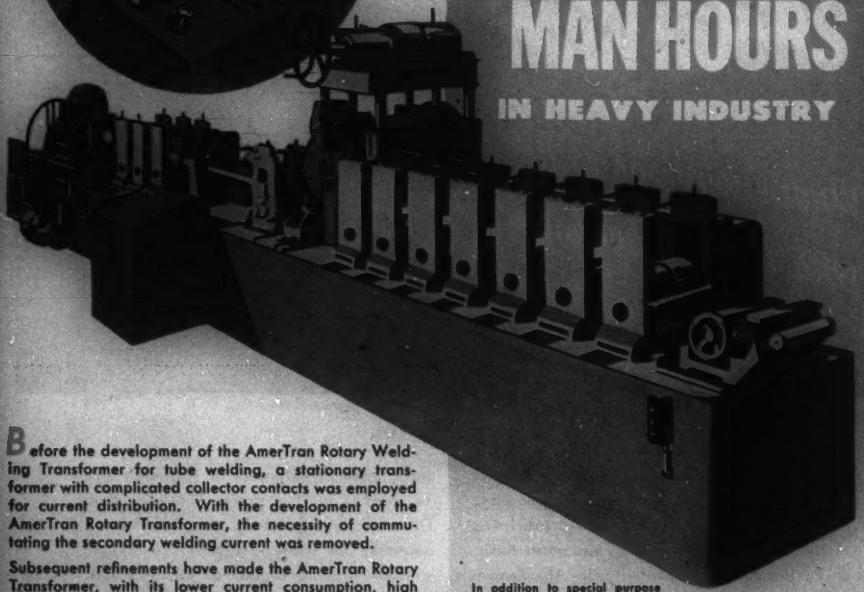
ALCOA A·C·S·R



AMERTRAN

FINDS LOST MAN HOURS

IN HEAVY INDUSTRY



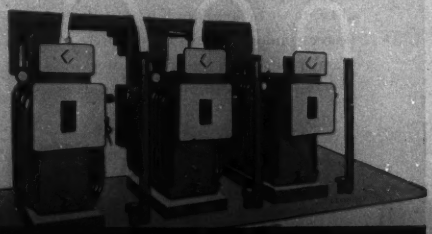
Before the development of the AmerTran Rotary Welding Transformer for tube welding, a stationary transformer with complicated collector contacts was employed for current distribution. With the development of the AmerTran Rotary Transformer, the necessity of commutating the secondary welding current was removed.

Subsequent refinements have made the AmerTran Rotary Transformer, with its lower current consumption, high power factor, small leads and positive non-leaking cooling, a most economical unit. Used in conjunction with the AmerTran Transtat Voltage Regulator, it is a most efficient power supply for tube welding.

This is merely one of the many instances where AmerTran transformer engineering has saved time and cut costs for heavy industries. Our versatile, flexible manufacturing facilities insure the speedy completion of even larger projects. And our long association with radio, as well, assures authoritative design and engineering service for your electronic control and rectifier needs. Write us today, outlining your problems.

AMERICAN TRANSFORMER COMPANY, 178 Emmet St., Newark 5, N. J.

In addition to special purpose transformers, the American Transformer Company manufactures a wide range of conventional types, such as the Abestol Immersed Distribution Transformers shown below.



Pioneer Manufacturers of Transformers, Reactors and Rectifiers for Electronics and Power Transmission

AMERTRAN

Wanted
ENGINEERS

- Radio
- Chemical
- Electrical
- Electronic
- Mechanical
- Metallurgical
- Factory Planning
- Materials Handling
- Manufacturing Planning

To be used in connection with the manufacture of a wide variety of new and advanced types of communications equipment and special electronic products.

Apply (or write), giving full qualifications, to:

C. R. L.
EMPLOYMENT DEPARTMENT
Western Electric Co.
100 CENTRAL AV., KEARNY, N. J.
Applicants must comply with WMC regulations

OPPORTUNITIES
WITH SPRAGUE

Wanted for production and product development:

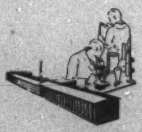
RESISTOR ENGINEER

The man to fill this position will need a good, practical working knowledge of resistance problems and a particular leaning toward the broad electrical field rather than radio alone. The work is interesting and has to deal with further development and expansion of the most unusual and most rapidly-growing resistor line.

JUNIOR ENGINEERS FOR QUALITY CONTROL

For this work, we need four or five practical men who are qualified, not only to check up on capacitor and resistor production, but who can also pick up a soldering iron or other tool on occasion and show how things should be done. Technically-informed men with better-than-average radio service or similar practical experience should find this a worthwhile opportunity.

WRITE AT ONCE if you feel that you can qualify for either of these positions. To the right men, Sprague offers interesting work, good living conditions and salaries in keeping with experience, plus worthwhile future opportunities made possible by planned post war developments of far-reaching importance.



Dept. EE, Personnel Section
North Adams, Mass.

SPRAGUE ELECTRIC COMPANY
(Formerly Sprague Specialties Company)

Applicants will, of course, be engaged only in strict compliance with regulations of the War Manpower Commission

Specialists for over a generation in

OIL IMMERSED MOTOR CONTROL

ROWAN CONTROL
THE ROWAN CONTROLLER CO., BALTIMORE, MD.

triple Six S

MODEL NO. 666S

All-Purpose Pocket Size Volt-Ohm-Milliammeter

A new modernistic styled, compact unit that provides an answer to all Volt-Ohm-Milliammeter requirements. Incorporates all the testing facilities of larger, more costly equipment. Self contained batteries. Selector switch control for all ranges. Completely insulated black molded case and panel. (Leather carrying case available for tester and accessories.)

Triplett
ELECTRICAL INSTRUMENT CO.
Bluffton Ohio ★★★

New...

"WATER BUFFALO" JOINS THE "FLEET"!

Packing the tremendous fire power of a 37-mm cannon and two 50 caliber machine guns this new LVT (A)-1 Amphibious Tank has already played a contributing role in successful invasions.

Agile on land and in water, this hard-hitting tank and all of its equipment, must be designed and constructed to meet unusual conditions—do a two-fold job.

Here hermetically sealed transformers are a must on all communications equipment.

Photo U. S. Navy

CHICAGO TRANSFORMER

DIVISION OF ESSEX WIRE CORPORATION

3501 WEST ADDISON STREET

CHICAGO, 18

A Trademark of the Pioneer

● Type 5CP1 is a mighty popular cathode-ray tube in the present war effort. It is required in large numbers for oscillographic and special indicating purposes. And DuMont is indeed proud to be producing its full share of 5CP's as still another contribution to victory, on the all-important electronic front.

Here again the specialized skill of DuMont engineers and craftsmen is in evidence. While adhering rigidly to standard specifications governing this popular type, DuMont has introduced its own refinements, improvements and double-check inspection for more rugged, longer-lasting cathode-ray tubes.

Always remember, when it bears the DuMont seal, it is the product of the pioneer in the *commercialized* cathode-ray tube and oscillography field.

● **Write for Literature . . .**

DUMONT

ALLEN B. DU MONT LABORATORIES, INC.

Passaic, New Jersey

Cable Address: Wespeslin, New York

FEDERAL POWER EQUIPMENT—well known for long dependable life, low cost, and high efficiency . . . made in a wide range of sizes and outputs . . . for any DC need from any AC source.

- **PUBLIC UTILITIES**—for station DC bus service, floating storage batteries and operating controls.
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★

Federal's exclusive CENTER CONTACT Selenium Rectifier discs provide new protection against corrosive atmosphere, are now in Federal Power Supply equipment. FIRST IN THE FIELD . . . STANDARD FOR INDUSTRY. *Write for Bulletins.*

The PLUS Answer to B2A Specifications

EXTRA HEAVY-DUTY CONTACTS PROVIDE BIG

SAFETY FACTOR

A SHOCK-PROOF RELAY...THAT'S *Really* SHOCK-PROOF!

If your problem is one of finding a B2A relay on which the contacts stay open or stay closed unfailingly under the most severe conditions of shock and vibration, write for details on Struthers-Dunn Type 17AXX. Small in size, light in weight, it meets and exceeds all specifications for such services.

Struthers-Dunn Nutcracker Type 61HXX100 answers the need for suitable relays for extreme services particularly where severe overloads may cause trouble on units on which contacts have a less generous heavy-duty safety factor. Typical applications include such services as controlling aircraft landing lights, or controlling a number of solenoids simultaneously.

These relays are compact and sturdy, have double-break contacts, and meet the latest 94-32185D specifications with contact safety factor to spare. By a simple system of removable links, they may be converted to meet any one of the earlier 94-32185 or 94-32185A, B, or C specifications—or, they can be supplied in their universal type which enables you to make your own adaptation, quickly and easily for *any* of these specifications.

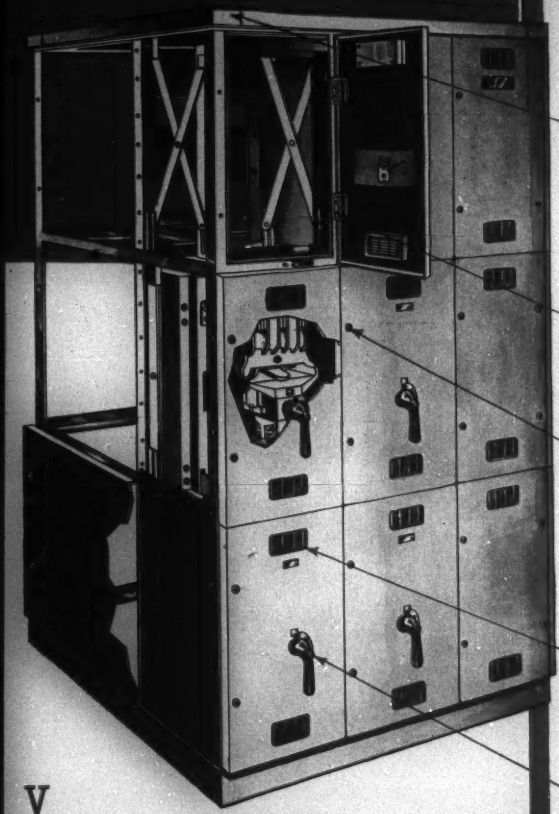
STRUTHERS-DUNN, INC., 1321 ARCH STREET, PHILADELPHIA 7, PA.

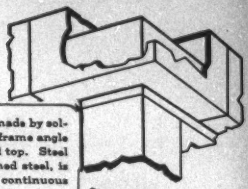
STRUTHERS-DUNN

5,288 RELAY TYPES

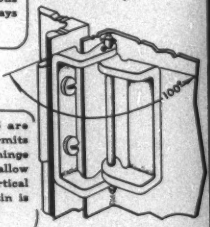
DISTRICT ENGINEERING OFFICES: ATLANTA • BALTIMORE • BOSTON • BUFFALO • CHICAGO • CINCINNATI • CLEVELAND
DALLAS • DENVER • DETROIT • HARTFORD • INDIANAPOLIS • LOS ANGELES • MINNEAPOLIS • MONTREAL
NEW YORK • PITTSBURGH • ST. LOUIS • SAN FRANCISCO • SEATTLE • SYRACUSE • TORONTO • WASHINGTON

IN DETAILS TOO – YOUR NEEDS GUIDE DESIGN OF I-T-E DRAWOUT SWITCHGEAR

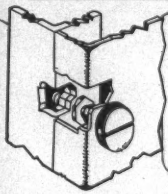




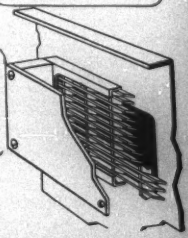
CORNERS are made by solidly welding frame angle to sheet-steel top. Steel trim, of formed steel, is added as a continuous finishing member always in alignment.



CONCEALED HINGES are sturdy. Design permits 100° swing. Slots in hinge and frame-angle allow horizontal and vertical alignment. Hingepin is readily removable.



PANEL SCREW has large head chamfered to prevent marring of finish. Palnut keeps screw attached to door at all times. Floating nut-block permits adjustment so that screw can be perfectly aligned with fastening thread.



LOUVERS are grille type, giving adequate air flow. Mounting is flush. Baffling is used when ventilating opening is close to arc chutes.

OPERATING HANDLE, mounted on front of door, disengages automatically when door is opened. Only 90° turn is required to close or trip the circuit breaker. Handle may be padlocked in open position.

You buy switchgear for long-term service. You want everything to be strong and dependable throughout. When a door is opened, you want it to swing far enough to give full access. To have ventilation, you want something more than a few holes "bumped" into a sheet of metal; you want louvers designed with plenty of engineering thought. With I-T-E switchgear you get careful design down to the last detail.

To plan switchgear, have a description of I-T-E design details at hand. Let an I-T-E engineer go over them with you. Have them written into your specifications. Descriptions are available in Bulletin 4207.

Representatives in Principal Cities

I-T-E

AIR SWITCHGEAR

IMMERSED IN AIR — ENCASED IN STEEL

ARMY E NAVY

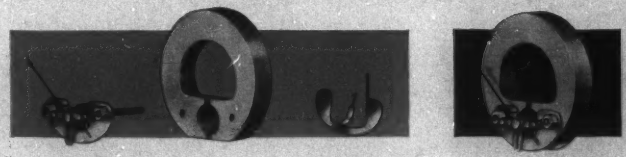
I-T-E

CIRCUIT BREAKER CO., PHILADELPHIA 30, PA.

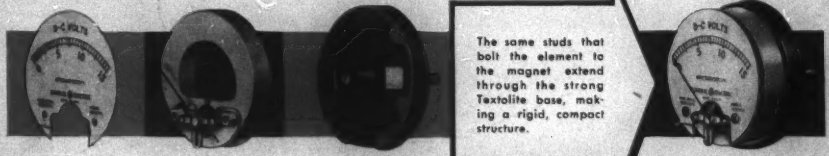
INTERNAL-PIVOT
2 1/2-inch PANEL INSTRUMENTS
...1 inch deep

SEE THE SIMPLICITY AND STRENGTH OF THEIR DESIGN

Note the few simple parts, and how strength is built in by solidly bolting the element to the one-piece, cast-comal magnet.



ELEMENT + MAGNET + BOTTOM BRIDGE = ELEMENT ASSEMBLY



The same studs that bolt the element to the magnet extend through the strong Textolite base, making a rigid, compact structure.

SCALE PLATE + ELEMENT ASSEMBLY + BASE ASSEMBLY = STRONG THIN INSTRUMENT

...built for tough jobs and long life

COMBAT service on aircraft and in military radio is the crucial test for any electric instrument. To meet the requirements of such severe service, G-E engineers went to extremes to gain simplicity and strength in the design of these new panel instruments.

What isn't shown clearly in the pictures above is the internal-pivot construction and how the pivots are mounted to the inside of the armature shell instead of being secured to the outside of the armature winding. The pivot shank actually extends through the armature shell, and is anchored firmly on both sides of the shell by pressing two brass washers over the pivot shank. This construction makes the entire element assembly 20 per cent thinner.

There are many other features: large-radius pivots, hard-glass jewels, good damping, and ample clearances between stationary and moving parts. Added up, these features give you an instrument well able to withstand vibration and hold its rated accuracy.

If you want the complete story of how these instruments pack all-round fine performance in a small space, ask our nearest office for Bulletin GEA-4064, which covers instruments used for radio and other communications equipment; or Bulletin GEA-4117 which describes those suitable for naval aircraft. *General Electric Co., Schenectady 5, N. Y.*

GENERAL ELECTRIC

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